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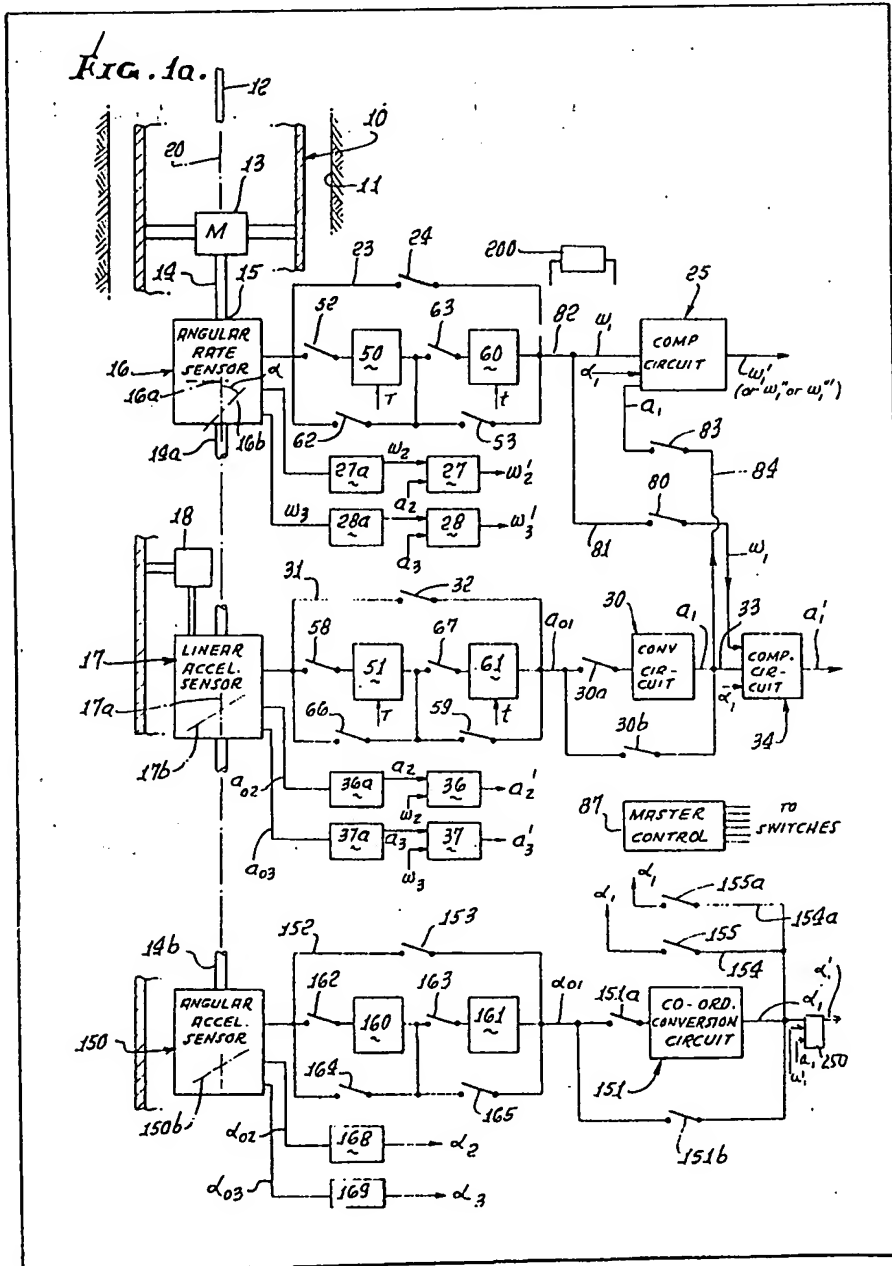
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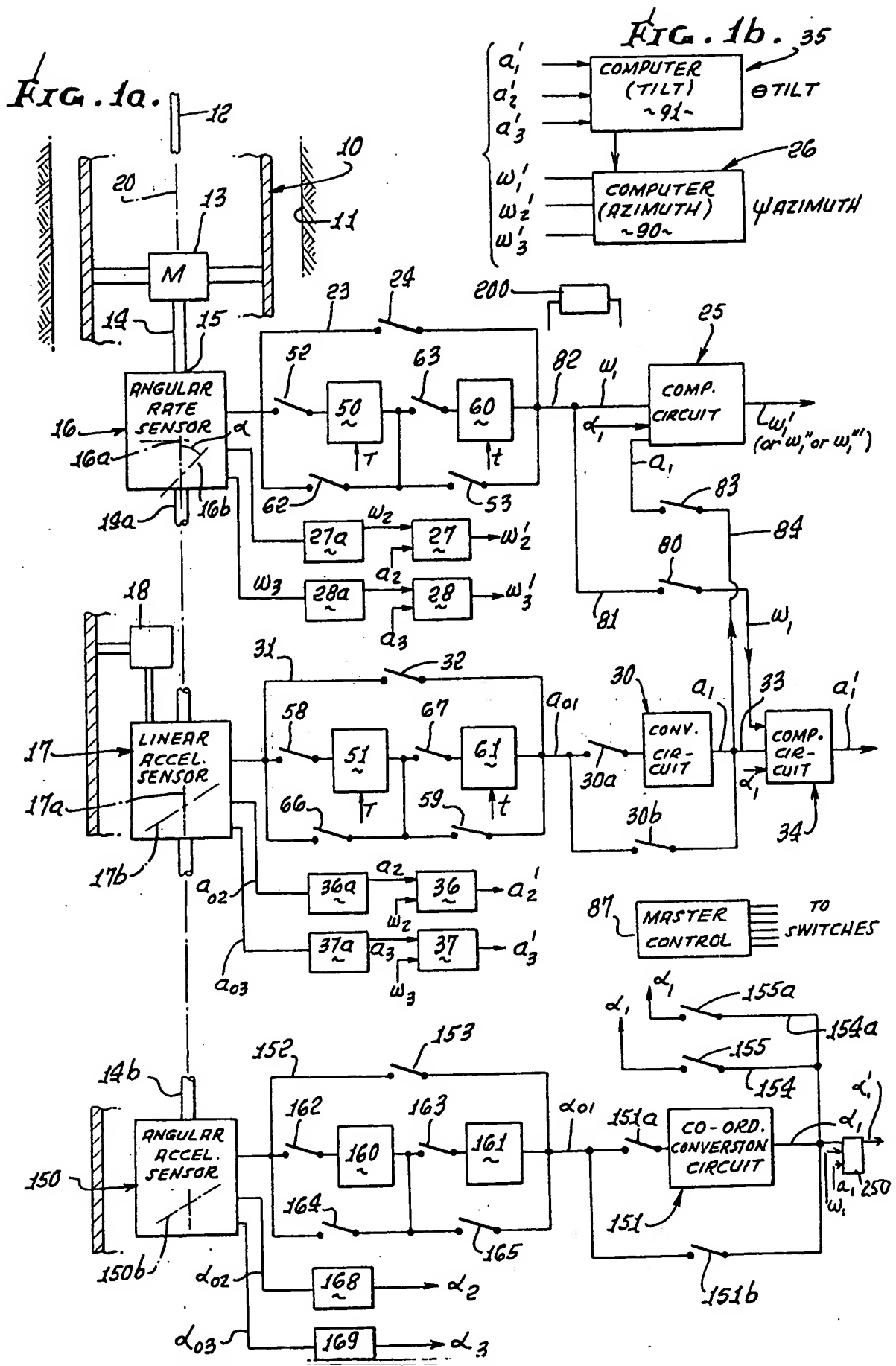
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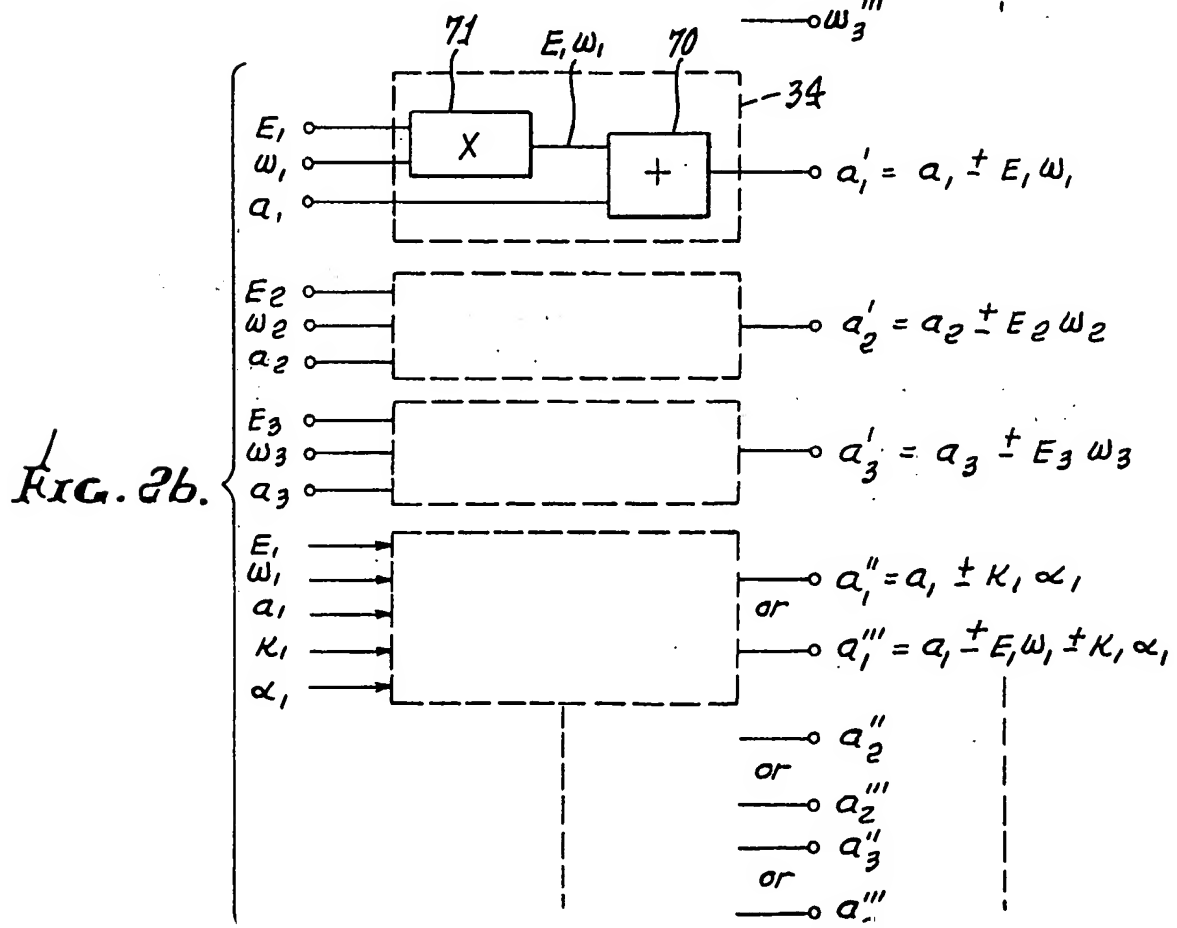
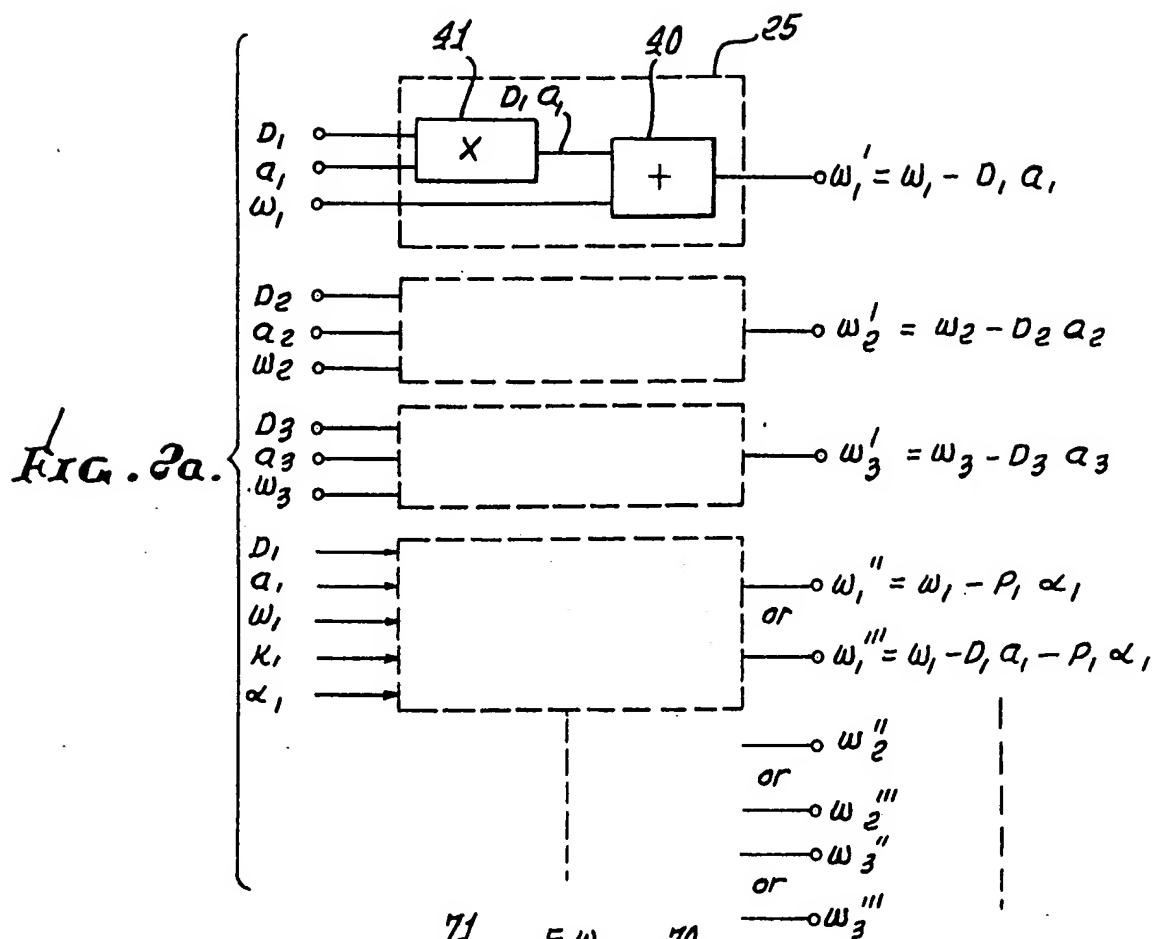
(54) Well mapping system with sensor output compensation

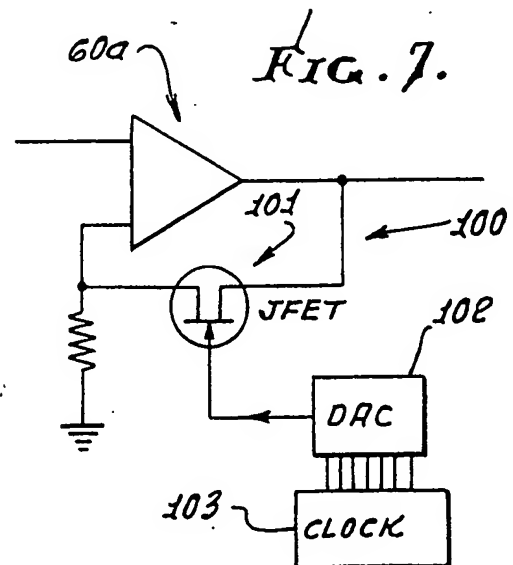
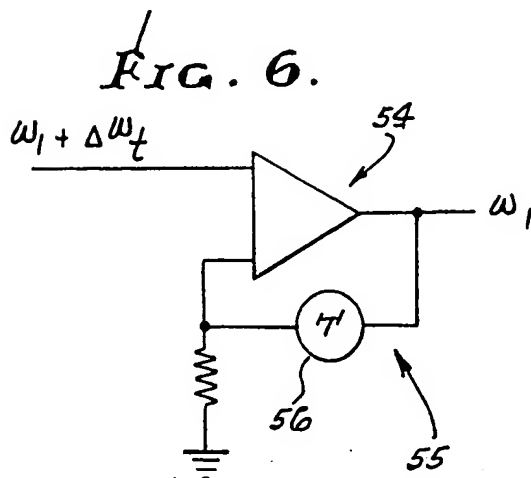
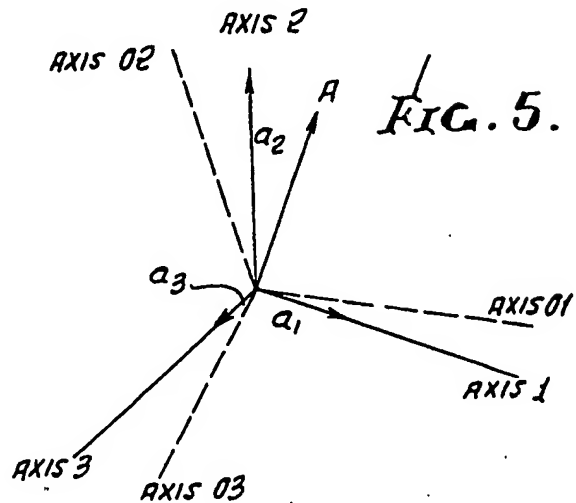
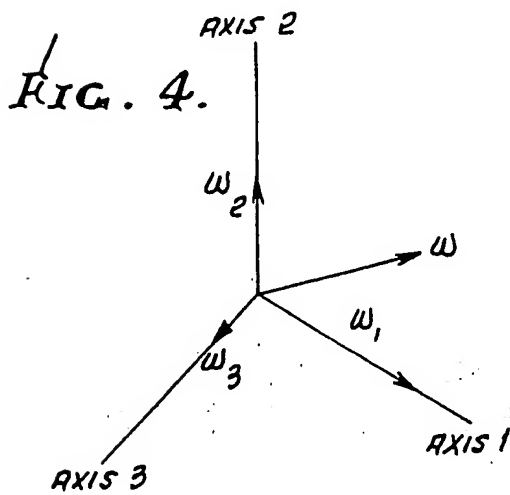
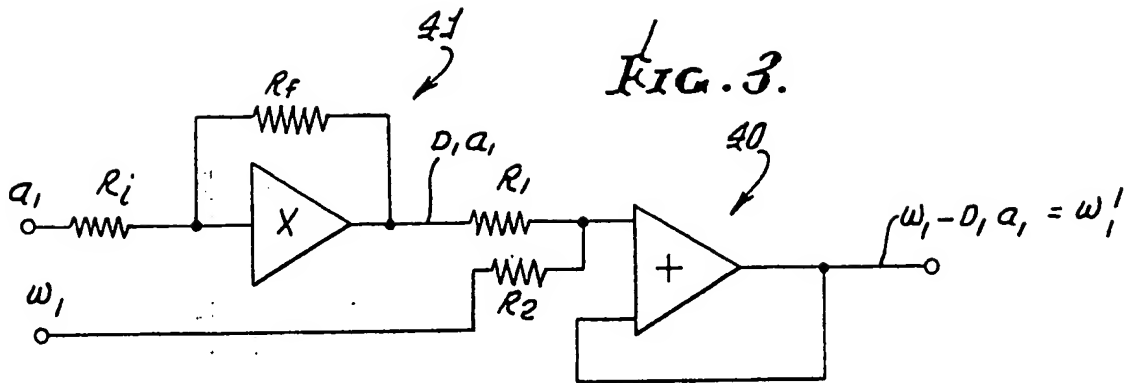
(57) Mapping, or surveying, in a borehole (11) is accomplished using selected combinations of sensors typically an angular rate sensor (16) a linear acceleration sensor (17) and an angular acceleration sensor (150), with circuit means (25, 27, 28, 34, 36, 37, 168, 169, 250) for compensating signals derived from the output of at least one of the sensors (e.g. 17) in accordance with

the values of signals derived from the outputs of the other sensors (16, 150), compensation being provided, in the hole or at the surface to correct certain errors for example bias errors, acceleration sensitive errors and acceleration squared errors and temperature and time induced errors. The sensor group is typically rotated in the bore-hole, and the sensors may have selected sensitive axis angularity (16*b*, 17*b*, 150*b*) relative to the travel axis (20) in the bore-hole. The apparatus is also applicable to tool steering in the bore hole.









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FIG. 8a.

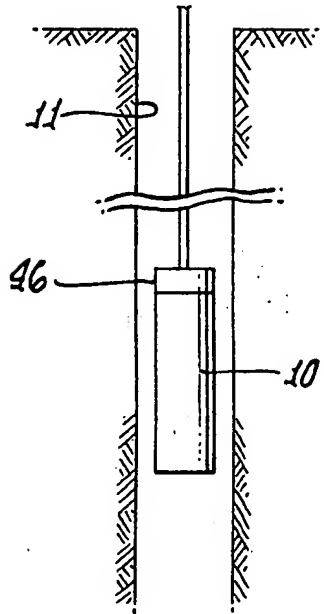


FIG. 8b.

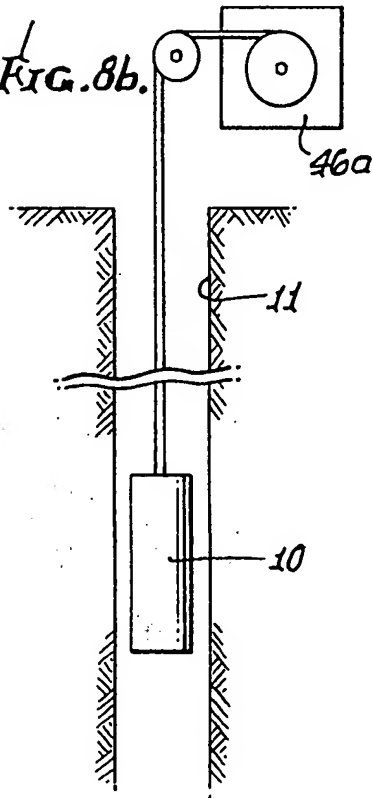


FIG. 8c.

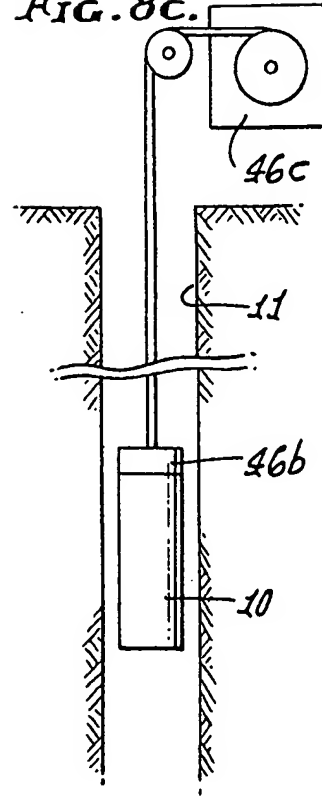


FIG. 18.

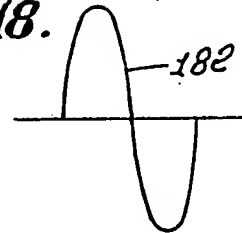
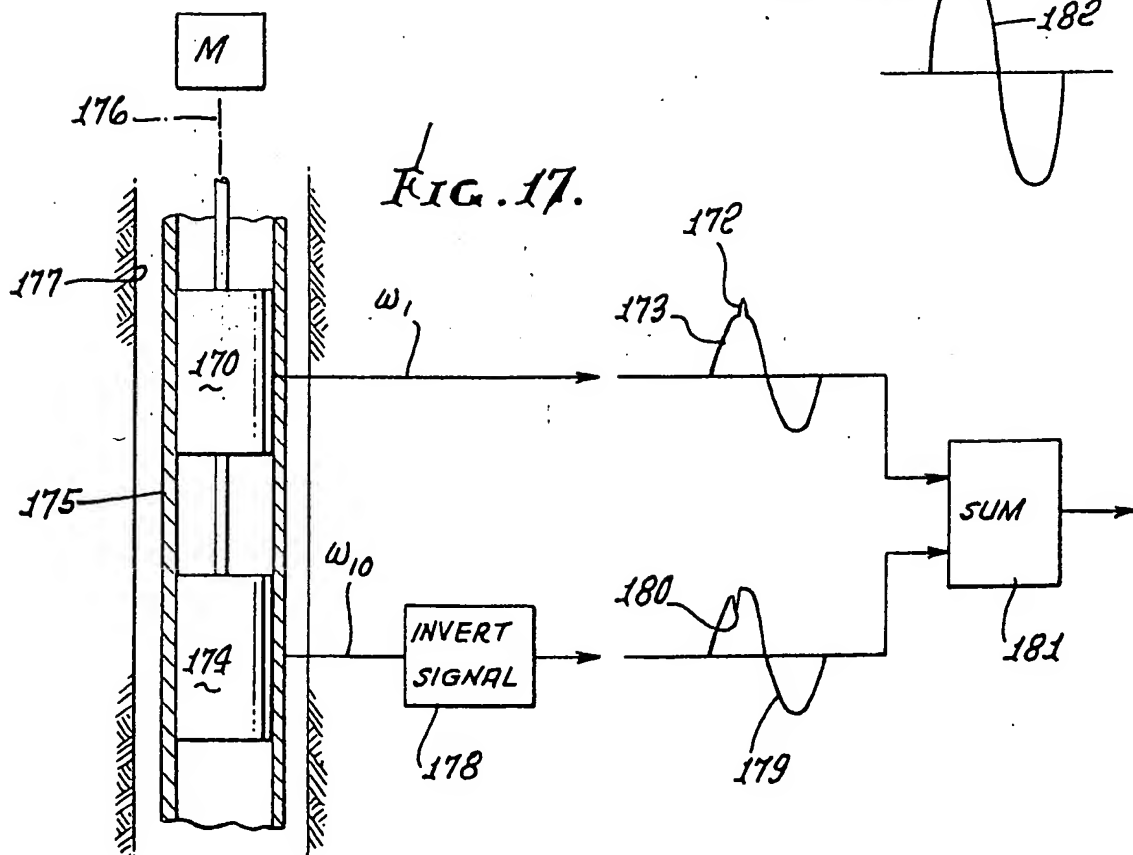
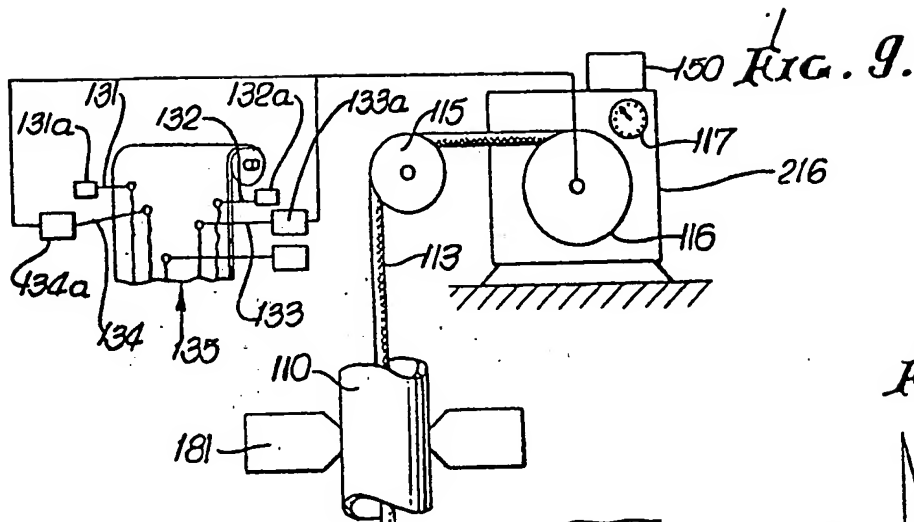
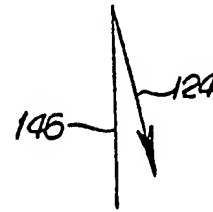
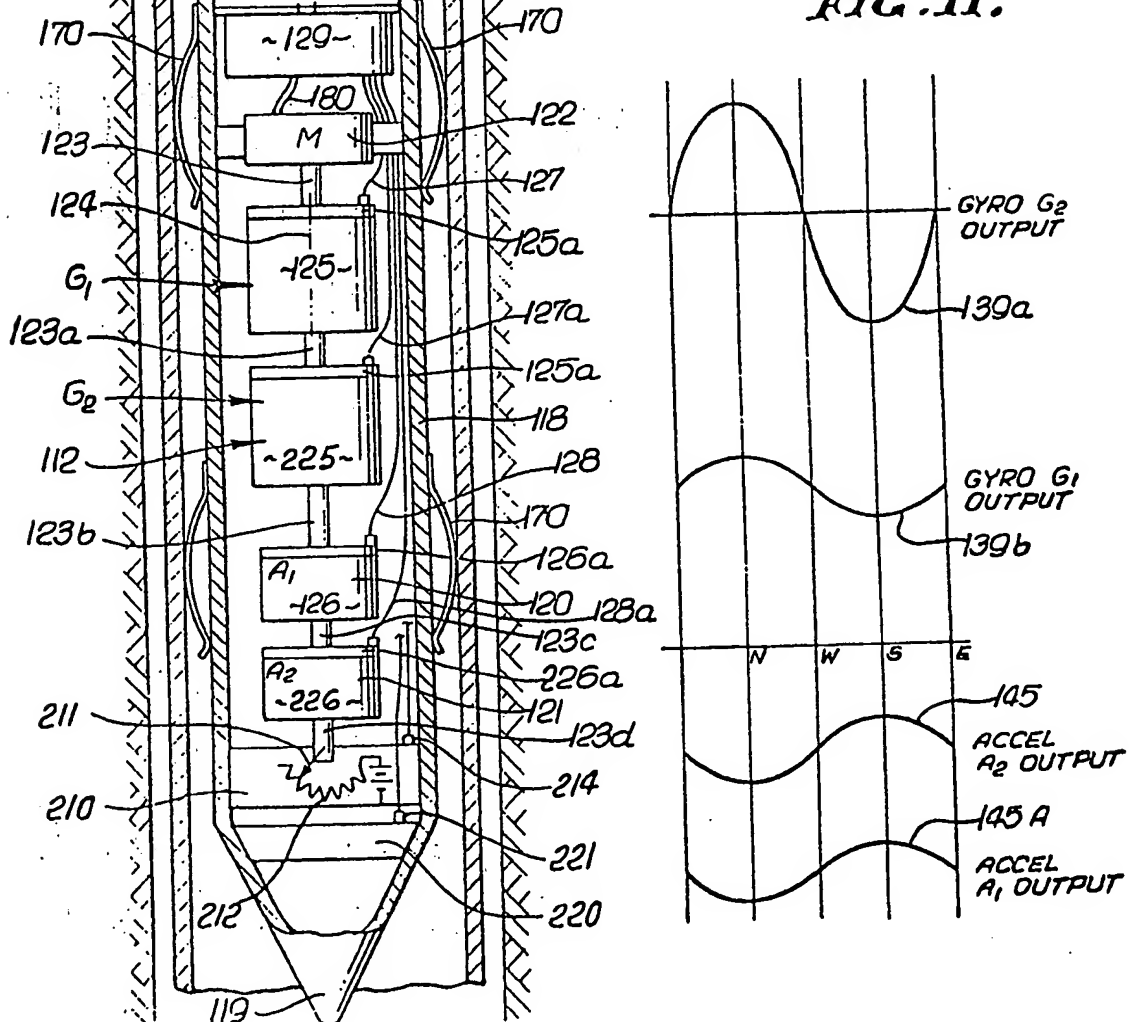
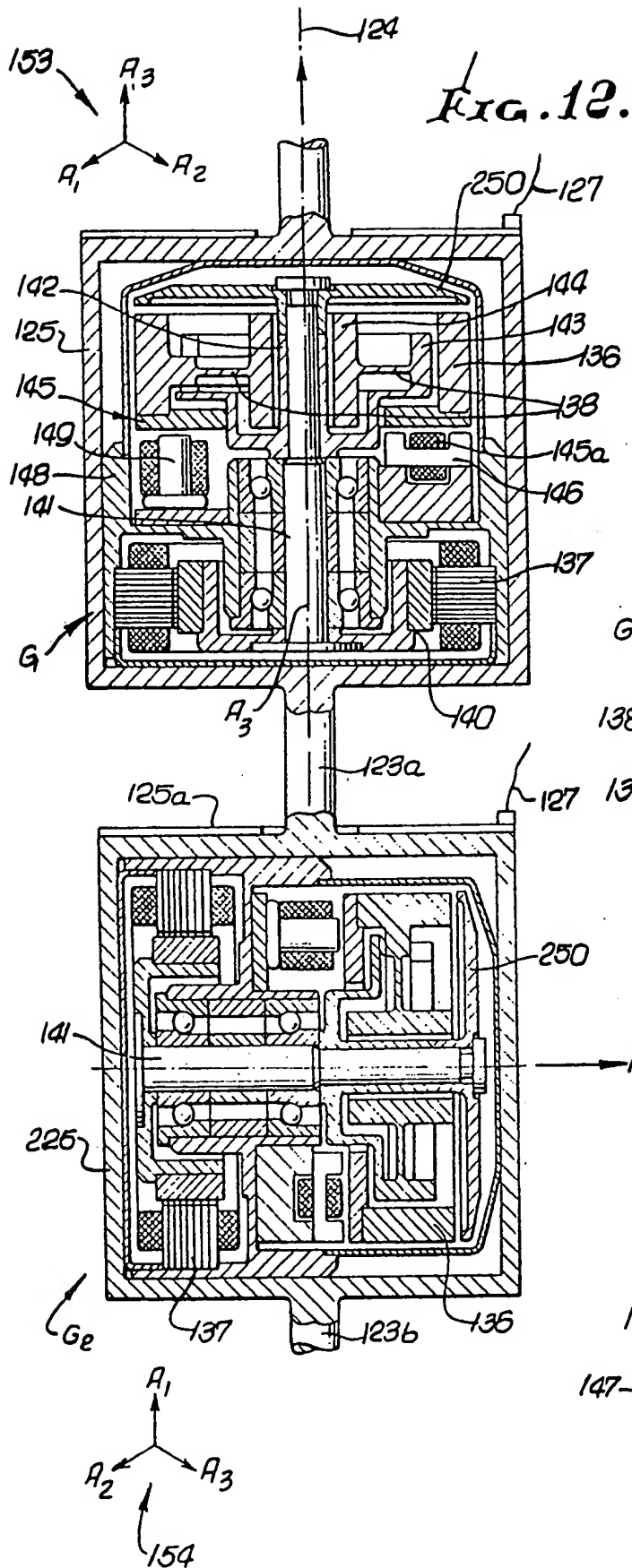
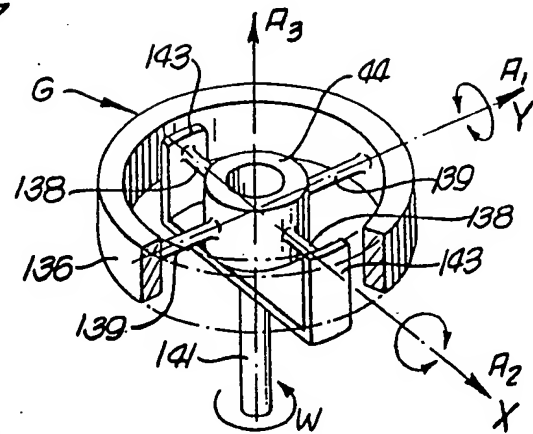
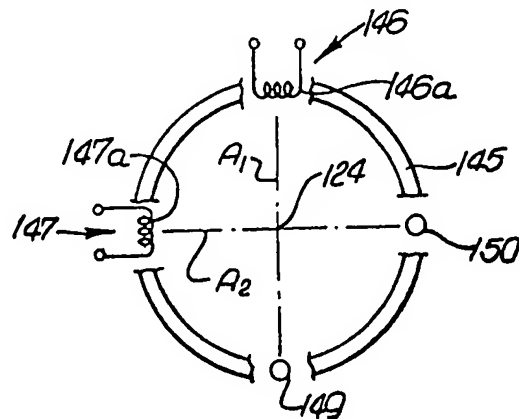


FIG. 17.



**FIG. 10.****FIG. 11.**

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**FIG. 12a.****FIG. 12b.**

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FIG. 14.

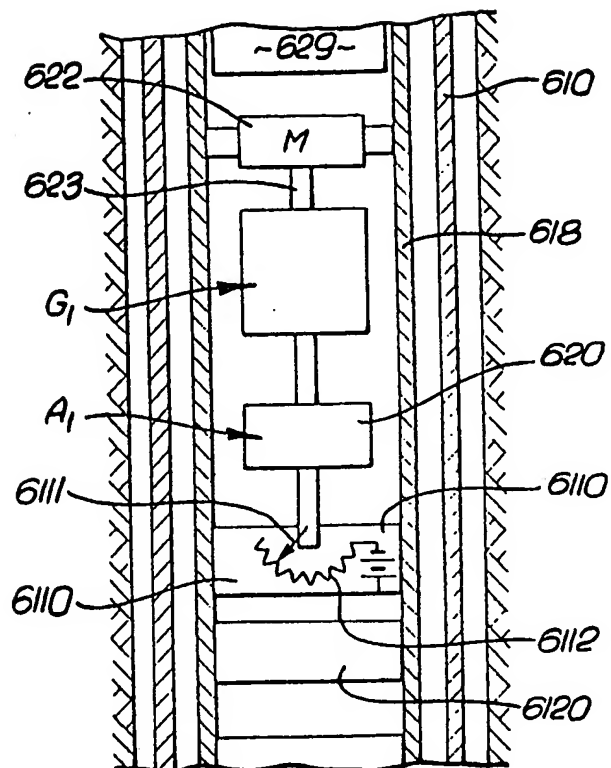


FIG. 13.

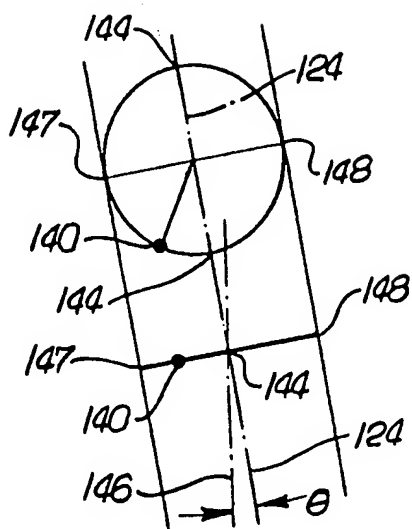


FIG. 15.

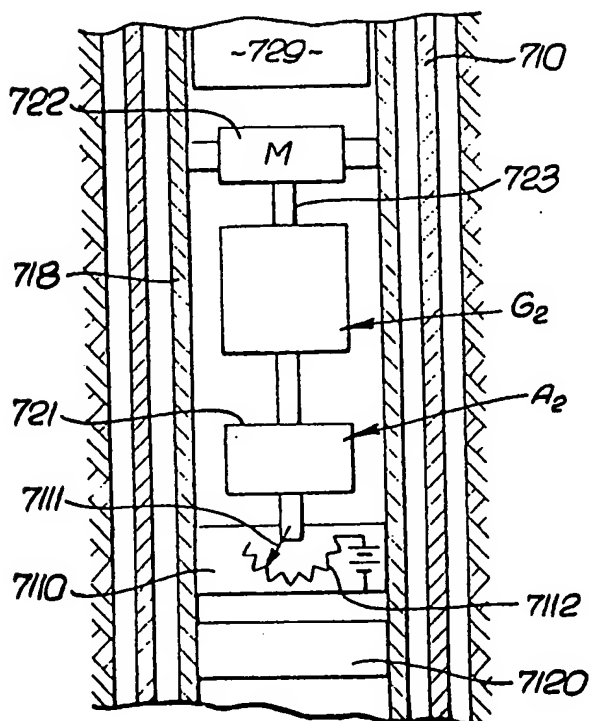
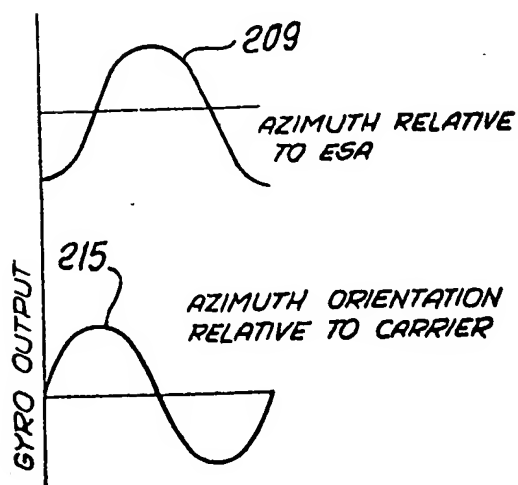
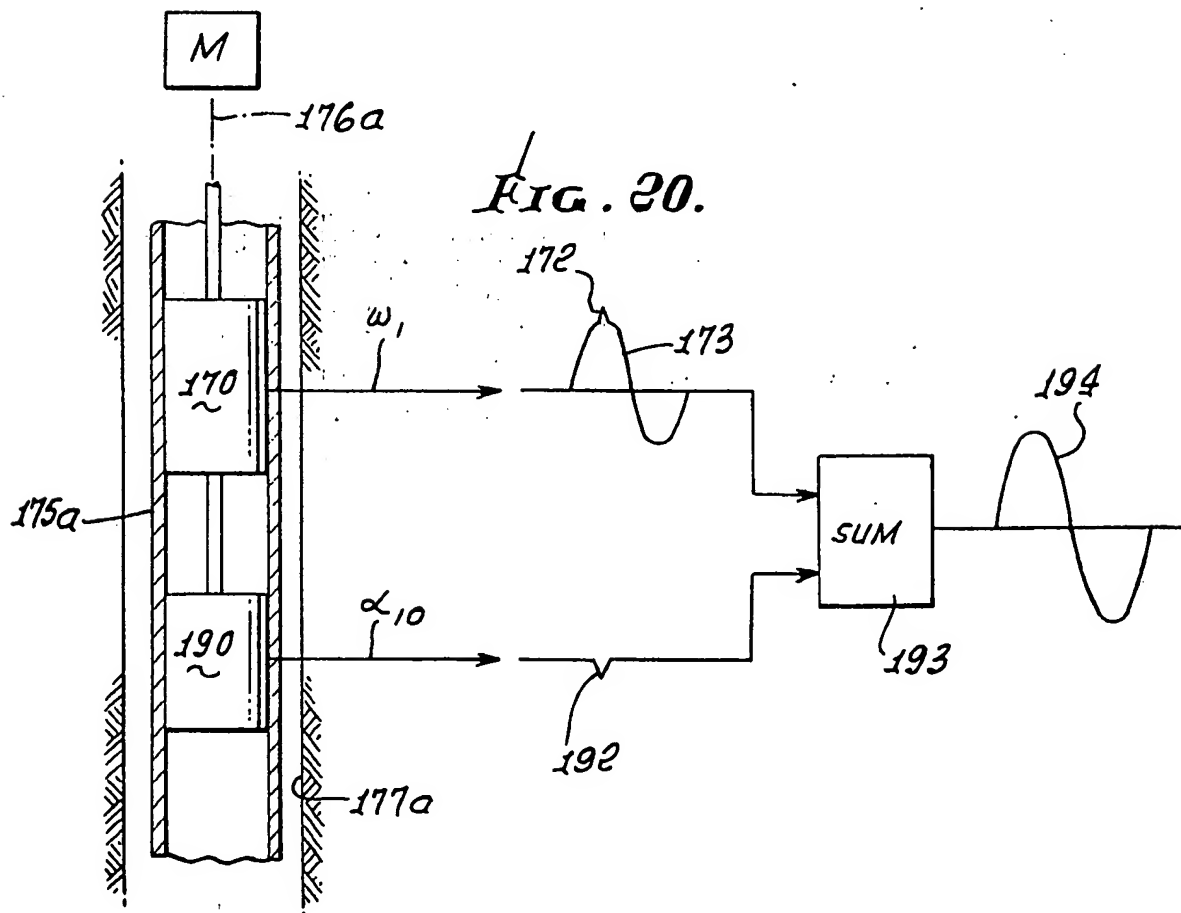
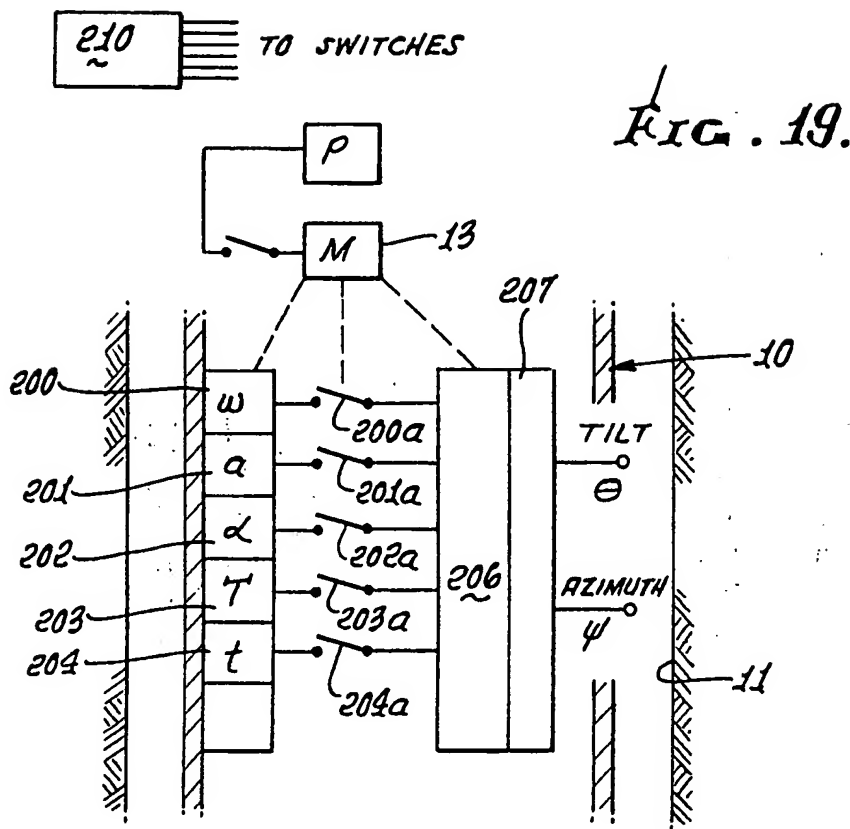


FIG. 16.



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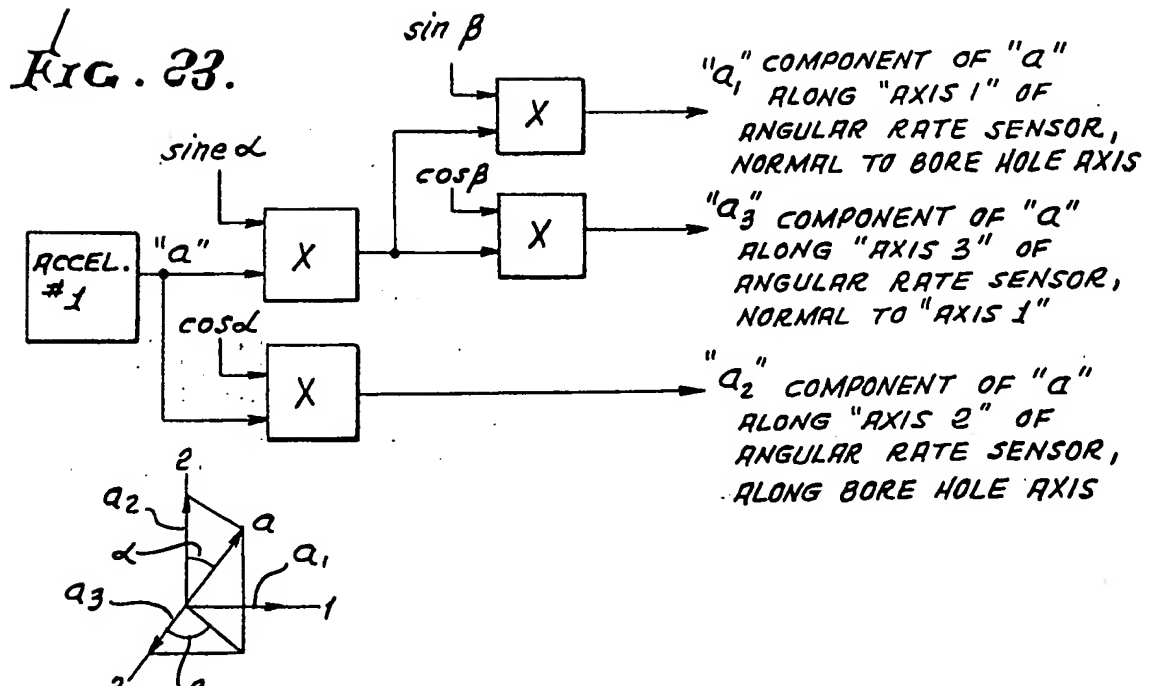
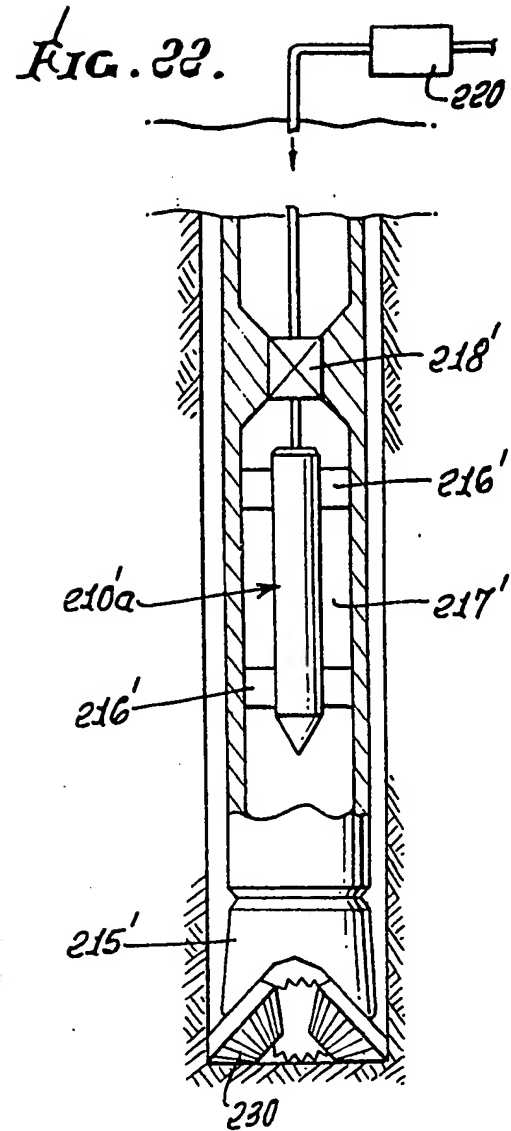
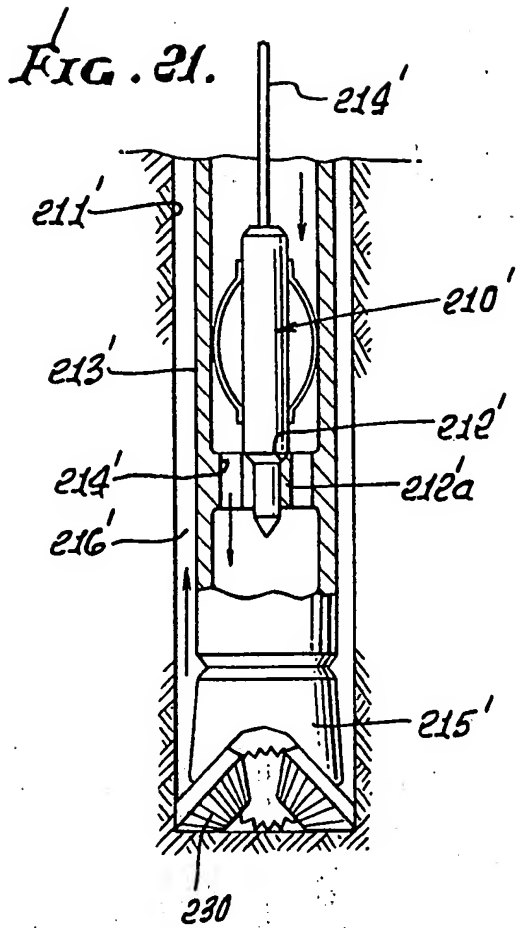


FIG. 28.

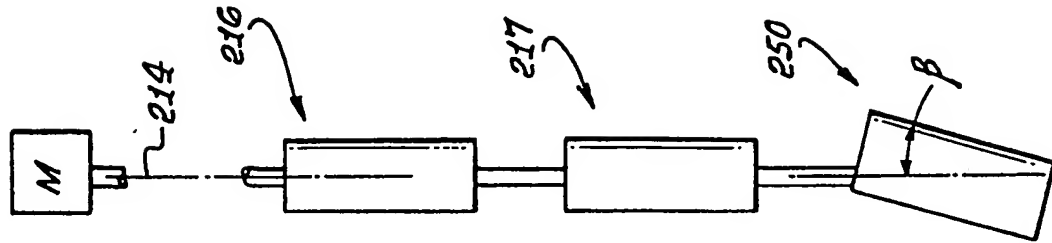


FIG. 27.

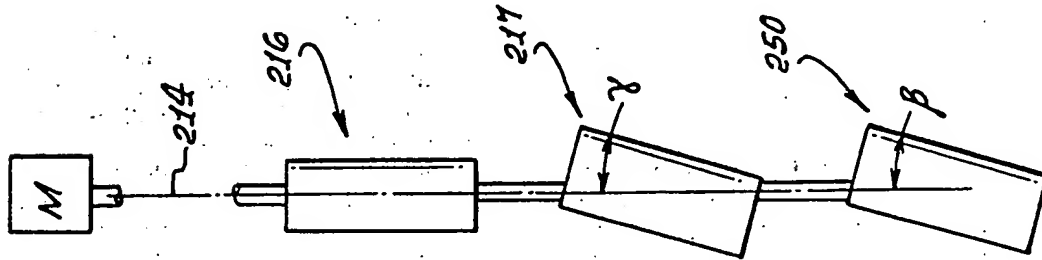


FIG. 26.

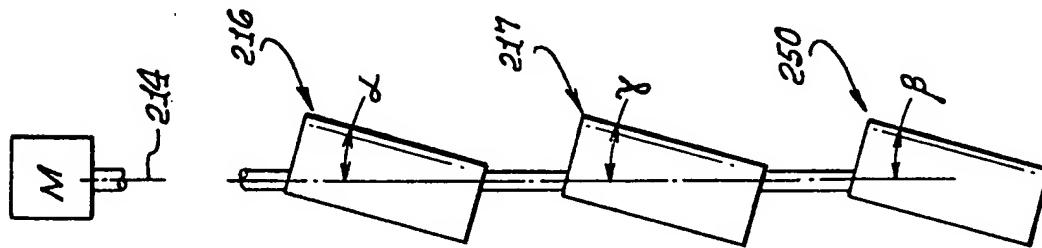


FIG. 25.

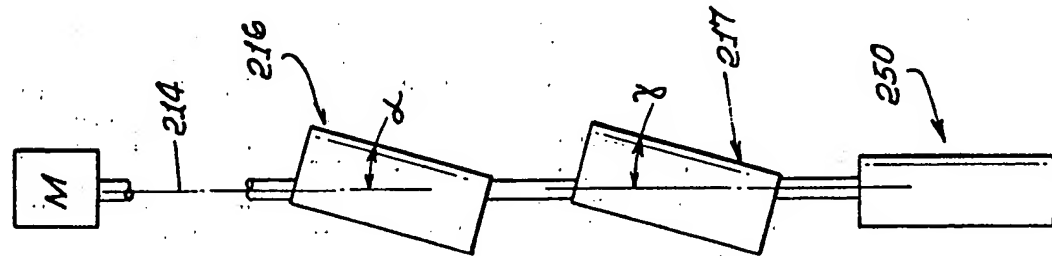
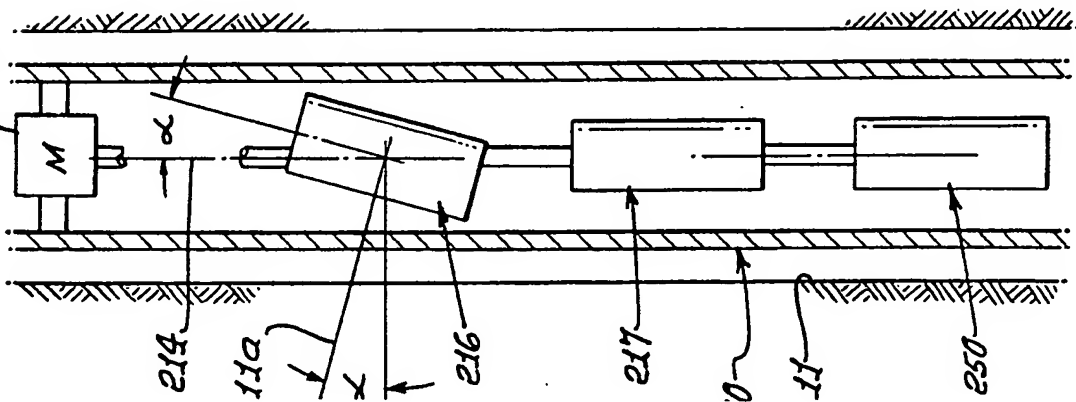


FIG. 24.



SPECIFICATION

Well mapping system and method with sensor output compensation

This invention relates generally to mapping apparatus and methods, and more particularly concerns well mapping employing a probe which may be inserted into a bore-hole or well, for surveying and/or for tool steering. In addition, it concerns method and apparatus to determine the probe's degree of tilt from vertical and to relate the latter to sensor generated azimuth information, at all latitudes and at all instrument attitudes. Further, the azimuth determining apparatus by itself or in combination with the tilt measuring apparatus, may be housed in a carrier of sufficiently small diameter to permit insertion directly into available small I.D. drill tubing, thus eliminating the need to remove the tubing to enable such mapping.

In the past, the task of position mapping a well or bore-hole for azimuth in addition to tilt has been excessively complicated, very expensive, and often inaccurate because of the difficulty in accommodating the size and special requirements of the available instrumentation. For example, magnetic compass devices typically require that the drill tubing be fitted with a few tubular sections of non-magnetic material, either initially or when drill bits are changed. The magnetic compass device is inserted within this non-magnetic section and the entire drill stem run into the hole as measurements are made. These non-magnetic sections are much more expensive than standard steel drill stem, and their availability at the drill site must be pre-planned. The devices are very inaccurate where drilling goes through magnetic materials, and are unusable where casing has been installed.

Directional or free gyroscopes are deployed much as the magnetic compass devices and function by attempting to remember a pre-set direction in space as they are run in the hole. Their ability to initially align is limited and difficult, and their capability to remember degrades with time and environmental exposure. Also, their accuracy is reduced as instrument size is reduced, as for example becomes necessary for small well bores. Further, the range of tilt and azimuthal variations over which they can be used is restricted by gimbal freedom which must be limited to prevent gimbal lock and consequent gyro tumbling.

A major advance toward overcoming these problems is described in U.S. Patent No. 3,753,296. That invention provides a method and means for overcoming the above complications, problems, and limitations by employing that kind and principal of a gyroscope known as a rate-of-turn gyroscope, or commonly 'a rate gyro', to remotely determine a plane containing the earth's spin axis (azimuth) while inserted in a bore-hole or well. The rate gyroscope has a rotor defining a spin axis; and means to support the gyroscope for travel in a bore-hole and to rotate about an axis extending in the direction of the hole, the gyroscope characterized as producing an output which varies as a function of azimuth orientation of the gyroscope relative to the earth's spin axis. Such means typically includes a carrier containing the gyroscope and a motor, the carrier being sized for travel in the well, as for example within the drill tubing. Also, circuitry is operatively connected with the motor and carrier to produce an output signal indicating azimuthal orientation of the rotating gyroscope relative to the carrier, whereby that signal and the gyroscope output may be processed to determine azimuth orientation of the carrier and any other instrument thereon relative to the earth's spin axis, such instrument for example comprising a well logging device such as a radiometer, inclinometer, etc.

U.S. Patent 4,199,869 improves upon 3,753,296 in that it provides for the obtaining of a very high degree of accuracy as respects derived azimuth and tilt information for all latitudes and angularities of bore-holes; the application of one or more two-degree of freedom gyroscopes as a "rate gyro" or rate gyros, for use in well mapping; the use of two such gyros in different attitudes to obtain cross-check azimuth information; and the provision of highly compact instrumentation which is especially needed for smaller diameter bore-holes.

While the devices of the above two patents are highly useful, they lack compensation for certain errors in the outputs of the angular rate sensor or sensors, and in the outputs of the tilt or acceleration sensor or sensors. Typical of such errors are bias errors, acceleration sensitive errors and acceleration squared errors, and temperature and time induced errors.

Typically, apparatus embodying the invention comprises:

- a) a carrier movable in the bore hole,
- b) angular rate sensor means on the carrier and having an output,
- c) an acceleration sensor means on the carrier and having an output, and
- d) circuit means operatively connected with the sensor means for compensating signals derived

from the output of at least one of the sensor means in accordance with the values of signals derived from the output of the other sensor means, to produce compensated signals.

As will be seen, the circuit means may be connected with the sensor means to adjust angular rate signals derived from the output of the angular rate sensor thereby to compensate for acceleration effects associated with acceleration signals derived from the output of the acceleration sensor means, so as to produce corrected angular rate values. Alternatively, or additionally, the circuit means may be connected with the sensor means to adjust acceleration signals derived from the output of the acceleration sensor means to compensate for angular rate effects associated with angular rate signals

derived from the output of the angular rate sensor means, thereby to produce corrected acceleration values.

In addition, temperature compensating circuit means may be provided to compensate signals derived from one or both of the sensors in accordance with temperature changes encountered in the bore-hole; and time compensating circuit means may also or alternatively be provided to compensate signals derived from one or both of the two sensor means, in accordance with time values. Such temperature and time corrections may be modeled, or calibrated, as functions of conditions encountered in the bore-hole.

Further, coordinate conversion circuit means may be operatively connected with the acceleration sensor means to convert output of the acceleration sensor means along three axes to values a_1 , a_2 and a_3 along three selected axes. Also, angular acceleration values may be obtained for compensation purposes.

Finally, means is provided to receive the corrected angular rate values and to produce an output which varies as a function of azimuth orientation of the angular rate sensor means.

Specific embodiments of the present invention in both its apparatus and method aspects will now be described by way of example and not by way of limitation with respect to the accompanying drawings, in which:

Fig. 1a is a block diagram;

Fig. 1b is a block diagram;

Fig. 2a is a block diagram;

Fig. 2b is a block diagram;

Fig. 3 is a circuit diagram;

Figs. 4 and 5 are co-ordinate diagrams;

Figs. 6 and 7 are circuit diagrams;

Figs. 8a—8c are elevations taken in bore-holes;

Fig. 9 is an elevation taken in section to show use of one form of instrumentation, in well mapping;

Fig. 10 is a diagram indicating tilt of the well mapping tool in a slanted well;

Fig. 11 is a wave form diagram;

Fig. 12 is an enlarged vertical section showing details of two gyrocompasses as may be used in

the apparatus of Fig. 9;

Fig. 12a is a diagrammatic representation of the G_1 accelerometer in Fig. 12;

Fig. 12b is a quadrant diagram;

Fig. 13 is a diagrammatic showing of the operation of one of the two accelerometers of Fig. 9, under instrument tilted conditions;

Fig. 14 is a view like Fig. 9 showing a modification in which one of the rate gyros of Fig. 4 is used;

Fig. 15 is a view like Fig. 9 showing a modification in which the other of the rate gyros of Fig. 12 is used;

Fig. 16 is a wave form diagram;

Fig. 17 is a schematic diagram;

Fig. 18 is a wave form diagram;

Fig. 19 is a schematic diagram;

Fig. 20 is a schematic diagram;

Figs. 21 and 22 are elevations showing use of the apparatus for drill steering;

Fig. 23 is a block diagram, and

Figs. 24—28 are elevations.

With reference to the accompanying drawings, Fig. 1a shows a carrier 10 movable in a bore-hole indicated at 11. Means to travel the carrier lengthwise in the hole is indicated at 12. A motor or other manipulatory means is indicated at 13 as carried by the carrier, and its rotary output shaft 14 is shown as connected at 15 to an angular rate sensor means 16. The shaft may be extended at 14a for connection to an acceleration sensor means 17. Alternatively, the means 17 may be manipulated by a motor or manipulator 18 also carried by the carrier 10.

The angular rate sensor means 16 may for example take the form of one or more of the following known devices; however, the term "angular rate sensor means" is not limited to such devices:

1. Single degree of freedom rate gyroscope

2. Tuned rotor rate gyroscope

3. Two axis rate gyroscope

4. Nuclear spin rate gyroscope

5. Sonic rate gyroscope

6. Vibrating rate gyroscope

7. Jet stream rate gyroscope

8. Rotating angular accelerometer

9. Integrating angular accelerometer

10. Differential position gyroscopes and platforms

11. Laser gyroscope

12. Combination rate gyroscope and linear accelerometer

Examples of angular rate sensors include the gyroscopes disclosed in U.S. Patents 3,753,296 and 4,199,869, having the functions disclosed therein. Each such device may be characterized as having a "sensitive axis" which is the axis about which rotation occurs to produce an output which is a measure of rate-of-turn or angular rate ω . That value may have components ω_1 , ω_2 , and ω_3 in a three axis coordinate system as shown in Fig. 4, for example. The sensitive axis may be generally normal to the axis 20 of instrument travel in the bore-hole (see sensitive axis 16a in Fig. 1a), or it may be canted at some angle α relative to axis 20 (see canted sensitive axis 16b in Fig. 1a).

The acceleration sensor means 17 may for example take the form of one or more of the following known devices; however, the term "acceleration sensor means" is not limited to such devices:

1. one or more single axis accelerometers
2. one or more dual axis accelerometers
3. one or more triple axis accelerometers

Examples of acceleration sensors include the accelerometers disclosed in U.S. Patents 3,753,296 and 4,199,869, having the functions disclosed therein. Such sensors may be supported to be orthogonal or canted relative to the carrier axis. They may be stationary or caroused, or may be otherwise manipulated, to enhance accuracy and/or gain an added axis or axes of sensitivity. An axis of sensitivity, viewed endwise, and normal to axis 20, is seen at 17a in Fig. 1a; and a canted axis of sensitivity is shown at 17b these being examples only. The axis of sensitivity is the axis along which acceleration measurement occurs. Sensitivity here is as to tilt.

Referring again to angular rate sensor 16, it may produce one output ω_1 , i.e. one output of angular rate, or it may produce two or three components, as for example the components of ω along the three axes shown in Fig. 4. Considering one component ω_1 , it may be directly passed via path 23 and switch 24 to input to the compensation circuit means 25. The latter processes ω_1 and produces a corresponding output ω'_1 . In Fig. 1b computer 26 receives inputs ω_1 , ω_2 , and ω_3 to produce azimuth output ω . Inputs ω'_2 and ω'_3 are derived from compensation circuits indicated at 27 and 28, and which correspond to circuitry 25.

In similar manner, the acceleration sensor 17 produces an output a_{01} which, after conversion at 30 become output a_1 . Output a_{01} is transmitted via path 31, which includes switch 32, to co-ordinate conversion circuit 30. If no conversion is required, circuit 30 is eliminated or by-passed (by opening switch 30a and closing switch 30b), and a_{01} becomes the same as a_1 . The sensor 17 may also produce component outputs a_{02} and a_{03} , which after conversion become a_2 and a_3 respectively. The sum of the component vectors corresponding to a_{01} , a_{02} and a_{03} equals the acceleration vector, and the sum of the component vectors a_1 , a_2 , and a_3 also equals the acceleration vector. The reason for converting to a_1 , a_2 and a_3 is to produce components in the same co-ordinate system as ω_1 , ω_2 and ω_3 , i.e. the ω system. See Fig. 5 in this regard. Circuitry 30 is well known, one resolver version being shown in Fig. 23, with multipliers as indicated. A similar co-ordinate conversion may be performed upon ω_1 , as by means 200 connectible in series in path 201, to convert ω_1 (and also ω_2 and ω_3) into coordinates the same as the coordinates of a_1 , a_2 , and a_3 ; and devices 30 and 200 may be used to convert into another or third coordinate system.

In Fig. 1a, output a_1 is directly passed via path 33 to input to the compensation circuit means 34. The latter processes a_1 and produces a corresponding output a'_1 . Computer 35 receives inputs a'_1 , a'_2 , and a'_3 to produce tilt output θ . Inputs a'_2 and a'_3 are derived from compensation circuits indicated at 36 and 37, and which correspond to circuitry 34.

Further, an angular acceleration sensor 150 may also be connected to shaft 14 via shaft extension 14b to be rotated with the sensors 16 and 17, and it may have its sensitive axis (about which angular acceleration is measured) parallel to the shaft 14 (generally parallel to the bore-hole), or canted relative thereto (see canted axis 150b).

The angular acceleration sensor produces an output α_{01} which, after co-ordinate conversion at 151 (like converter 30) becomes output α_1 . Output α_{01} is transmitted via path 152, which includes switch 153, to co-ordinate conversion circuit 151. If no conversion is required, circuit 151 is eliminated or by-passed (by opening switch 151a and closing switch 151b), and α_{01} then becomes the same as α_1 . The sensor 150 may also produce component outputs α_{02} and α_{03} , which after conversion become α_2 and α_3 respectively. The sum of the component vectors corresponding to α_{01} , α_{02} and α_{03} equals the angular acceleration vector, and the sum of the converted vectors α_1 , α_2 and α_3 also equals the angular acceleration vector. Such conversion produces components in the same co-ordinate system as ω_1 , ω_2 and ω_3 , i.e. the " ω " system. Devices 30, 200 and 151 may be used to convert into another or third co-ordinate system.

Any of the compensation circuits 25, 27, 28, 34, 36 and 37 may be regarded as a compensation means operatively connected with the sensor means (as for example sensor 16, 17 and 150) for compensating signals derived from the output of at least one of the sensor means (one of 16, 17 and 150, for example) in accordance with values of signals derived from other of the sensor means (the others of 16, 17 and 150, for example), to produce compensated signals. Thus, for example the circuit means is connected with the sensor means to adjust angular rate signals derived from the output of the angular rate sensor thereby to compensate for acceleration effects associated with acceleration signals derived from the output of the acceleration sensor means, so as to produce corrected angular rate

values. The compensation means may be indicated at 25 to adjust angular rate signals ω_1 derived from the output of the angular rate sensor 16, thereby to compensate for acceleration effects associated with acceleration signals (as at a_1) derived from the output of the acceleration sensor means, to produce corrected angular rate values, ω'_1 . This correction removes the influence of gravity from the angular rate value, for example. Also, corrected values ω'_1 and ω''_1 may be produced, as described.

Referring to Fig. 2a the compensating circuit 25 may typically include summing circuitry at 40 to sum an angular rate signal ω_1 along a selected coordinate axis (axis 1 for example), and a signal $D_1 a_1$ along that axis, where D_1 is a constant and a_1 is a value corresponding to the output of the acceleration sensor 17. The value $D_1 a_1$ is produced by a multiplying circuit 41 in Fig. 2a, the inputs to which are D_1 and a_1 , as indicated, and the output of circuit 40 is the compensated value $\omega'_1 = \omega_1 - D_1 a_1$. Similar compensated output values $\omega'_2 = \omega_2 - D_2 a_2$ along axis 2, and $\omega'_3 = \omega_3 - D_3 a_3$ are shown in Fig. 1. D_1 may be generated in circuit 25, for example, D_2 may be generated in 27, and D_3 in 28. Fig. 3 shows one specific form of circuitry 40 and 41, in the form of summing and multiplying amplifiers, although digital devices may alternatively be employed. In amplifier 41,

$$D_1 = 1 + \frac{R_f}{R_i}$$

the resistors R_f and R_i being connected as shown.

In Fig. 1a, output α_1 from angular acceleration sensor 150 is directly and selectively passed via path 154 and switch 155 to the compensation circuit 25, and via path 154a and switch 155a to the compensation circuit 34. When passed to circuit 25, it compensates the angular rate ω_1 to produce compensated output value $\omega''_1 = \omega_1 - P_1 \alpha_1$, and where ω_1 is also compensated by linear acceleration a_1 , then the compensated output value becomes $\omega''_1 = \theta_1 - D_1 a_1 - P_1 \alpha_1$. In other words, the output of the angular rate sensor is compensated for both linear and angular acceleration values. In similar manner, the output α_2 may be used to produce $\omega''_2 = \omega_2 - P_2 \alpha_2$, and $\omega''_2 = \omega_2 - D_2 a_2 - P_2 \alpha_2$, and the output α_3 may be used to produce $\omega''_3 = \omega_3 - P_3 \alpha_3$, and $\omega''_3 = \omega_3 - D_3 a_3 - P_3 \alpha_3$.

Also associated with the apparatus of Fig. 1a is temperature compensating circuit means to compensate signals derived from at least one, or both, of the sensors 16 and 17 in accordance with temperature changes encountered in the bore-hole. See for example the circuitry 50 associated with sensor 16, and circuitry 51 associated with sensor 17. When switches 52 and 53 are closed, and switch 24 open, the output of sensor 16 passes through circuitry 50 and to compensating circuitry 25 previously discussed. Thus, if the output of sensor 16 is undesirably increased by an amount $\Delta\omega_T$ due to bore-hole high temperature, the circuitry 50 eliminates $\Delta\omega_T$ from that output. Known circuitry to produce such compensation may take the general form of the amplifier 54 in Fig. 6, having a feedback circuit 55 with a thermistor 56 connected as shown, this being one example only. Thermistor 56 is exposed to sensor temperature. A similar temperature compensating circuit 51 and switches 58 and 59, are shown in association with sensor 17, to suppress temperature increases Δa_1 added to the output a_1 of sensor 17.

In addition, time compensating circuit means is shown in association with the sensors 16 and 17 to compensate their outputs in accordance with selected time values. See for example the time compensating circuit 60 associated with sensor 16, and circuit 61 associated with sensor 17. When switches 62 and 63 are closed, and switches 52, 24 and 53 are open, the output of sensor 16 passes through circuitry 60, and to compensation circuitry 25 discussed above. Thus, for example, if the voltage output of sensor 16 degrades or diminishes in amplitude over a period of time, it may be restored by circuit 60. Fig. 7 shows one example of a time compensating (gain restorative) circuit with a feedback circuit 100 containing JFET 101 controlled by digital-to-analog converter 102 driven by clock 103. There are other examples of time compensation, including phase shift, etc.

If desired, switches 52 and 63 may be closed and switches 24, 62 and 63 opened, to pass the output of 16 through both compensators 50 and 60 for both temperature and time compensation.

Similar time compensation switches are shown at 36 and 37 in association with sensor 17.

The temperature and time compensation circuits for the output of sensor 150 appear at 160 and 161 (and correspond to 51 and 61) and switches appear at 162, 163, 164 and 165 and 166 to correspond to switches 58, 67, 66 and 59. Each of blocks 168 and 169 respectively in series with inputs α_{02} and α_{03} represents temperature and time circuits, like 160 and 161, and associated switches.

The above discussed compensation means 34 is shown as operatively and selectively connected with the sensors 16, 17 and 150 to adjust acceleration signals a_1 derived from the output of the acceleration sensor 17 to compensate for angular rate effects associated with angular rate signals ω_1 derived from the output of the angular rate sensor 16, and also to selectively compensate for angular acceleration effects associated with angular acceleration signals α_1 derived from sensor 150, thereby to produce corrected acceleration values a'_1 . Referring to Fig. 2b, the compensator 34 may be similar to compensator 25 (Fig. 2a) in that it also includes a summing circuit 70 to sum a_1 and $E_1 \omega_1$, and a multiplier circuit 71 to receive E_1 and ω_1 and produce the product $E_1 \omega_1$, where E_1 is a selected constant.

Thus, corrected $a'_1 = a_1 \pm E_1 \omega_1$. The value E_1 may for example be a calibrating value such as to produce the desired a'_1 which is found in practice to be influenced by ω_1 . Compensation circuits like 34 are provided at 36 and 37 to respectively produce:

$$a'_2 = a_2 \pm E_2 \omega_2,$$

5 and

$$a'_3 = a_3 \pm E_3 \omega_3$$

If the angular acceleration correction is used, then the following corrected linear acceleration values are achieved:

$$a''_1 = a_1 \pm K_1 \alpha_1$$

10

10

$$a''_2 = a_2 \pm K_2 \alpha_2$$

$$a''_3 = a_3 \pm K_3 \alpha_3$$

or, alternatively, for both $\omega + \alpha$ correction:

$$a'''_1 = a_1 \pm E_1 \omega_1 \pm K_1 \alpha_1$$

$$a'''_2 = a_2 \pm E_2 \omega_2 \pm K_2 \alpha_2$$

15

$$a'''_3 = a_3 \pm E_3 \omega_3 \pm K_3 \alpha_3$$

15

Similarly, compensation means 250 is shown as operatively and selectively connectible with the sensors 16, 17 and 150 to adjust angular acceleration signals α_1 derived from the output of the angular acceleration sensor 150 to compensate for angular rate effects associated with angular, rate signals ω_1 derived from the output of the angular rate sensor 16, and also to selectively compensate for linear acceleration effects associated with acceleration signals a_1 derived from sensor 17, thereby to produce corrected angular acceleration values α'_1 . The compensator 250 may be similar to compensator 25 (Fig. 2a) in that it also includes a summing circuit and a multiplier circuit to receive F_1 and ω_1 and produce the product $F_1 \omega_1$, where F_1 is a selected constant. Thus, corrected $\alpha'_1 = \alpha_1 \pm F_1 \omega_1$. The value F_1 may for example be a calibrating value such as to produce the desired α'_1 , which is found in practice to be influenced by ω_1 . Compensation circuits like 250 are similarly provided to respectively produce:

$$\alpha'_2 = \alpha_2 \pm F_2 \omega_2,$$

and

$$\alpha'_3 = \alpha_3 \pm F_3 \omega_3$$

Correction for both ω and "a" may be provided in the manner discussed above. Each of block 27a and 28a respectively in series with compensation circuits 27 and 28 represents temperature and time circuits like 50 and 60 and associated switches. Likewise, each of blocks 36a and 37a respectively in series with compensation circuits 36 and 37 represents circuits like 51, 61, 30 and associated switches. Blocks 27 and 36 have cross over connections corresponding to connections 81 and 84, and blocks 28 and 37 also have such cross-over connections. Each of blocks 168 and 169 corresponds to the temperature and time compensators 160 and 161.

Note also in Fig. 1a the switch 80 in the cross-over path 81 extending from the ω_1 input path 82 to compensator 25, to provide ω_1 input to compensator 34; and the switch 83 in the cross-over path 84 extending from the a_1 input path 33 to compensator 34, to provide a_1 input to compensator 25.

Some or all of the switches shown in Fig. 1a may be suitably and selectively controlled from a master control 87, either in the bore-hole or at the bore-hole surface. Thus, for example, either or both of the compensators 25 and 34 may be employed to compensate as described, by control of switches 80 and 83; and various ones or combinations of the temperature and time compensators may be employed, or excluded, by selective operation of the switches associated therewith, as described and shown.

The described circuitry connected to the outputs of the sensors 16 and 17 may be located in the bore-hole (as on the carrier) outside the bore-hole (as at the well surface) or partly in the hole and partly out. See for example Fig. 8a showing such circuitry at 46 on the carrier 10 in the bore-hole 11; Fig. 8b showing such circuitry at 46a outside the hole; and Fig. 8c showing such circuitry one part 46b of which is on the carrier in the hole and another part 46c of which is at the well surface, outside the hole.

Fig. 1b shows circuit means, such as a computer 90, connected with one or more of the compensation circuits 25, 27 and 28, to receive corrected angular rate values ω'_1 , ω'_2 and ω'_3 and to produce an output which varies as a function of azimuth orientation of the sensor 16. Operation of the computer is as generally described below. Also, Fig. 1b shows circuit means, such as a computer 91, connected with one or more of the compensation circuits 34, 36 and 37 to receive corrected acceleration values a'_1 , a'_2 and a'_3 , and to produce an output which varies as a function of tilt of the acceleration sensor means. Operation of the computer 91 is as generally described below.

The compensation principles as discussed above may be applied not only to a system which includes one angular rate sensor, but also to two or more angular rate sensors, each or either of which may be connected in compensating relation with an accelerometer or tilt detector. Thus, one or more accelerometers may be employed. Figs. 9—16 below, and their accompanying description, refer to a two angular rate sensor system, wherein rate gyroscopes are employed.

In Fig. 9, well tubing 110 extends downwardly in a well 111, which may or may not be cased. Extending within the tubing is a well mapping instrument or apparatus 112 for determining the direction of tilt, from vertical, of the well or bore-hole. Such apparatus may readily be traveled up and down in the well, as by lifting and lowering of a cable 113 attached to the top 114 of the instrument. The upper end of the cable is turned at 115 and spooled at 116, where a suitable meter 117 may record the length of cable extending downwardly in the well, for logging purposes.

The apparatus 112 is shown to include a generally vertically elongated tubular housing or carrier 118 of diameter less than that of the tubing bore, so that well fluid in the tubing may readily pass, relatively, the instrument as it is lowered in the tubing. Also, the lower terminal of the housing may be tapered at 119, for assisting downward travel or penetration of the instrument through well liquid in the tubing. The carrier 118 supports first and second angular sensors such as rate gyroscopes G_1 and G_2 , and accelerometers 120 and 121, and drive means 122 to rotate the latter, for travel lengthwise in the well. Bowed springs 170 on the carrier center it in the tubing 110.

The drive means 122 may include an electric motor and speed reducer functioning to rotate a shaft 123 relatively slowly about a common axis 124 which is generally parallel to the length axis of the tubular carrier, i.e. axis 124 is vertical when the instrument is vertical, and axis 124 is tilted at the same angle from vertical as is the instrument when the latter bears sidewardly against the bore of the tubing 110 when such tubing assumes the same tilt angle due to bore-hole tilt from vertical. Merely as illustrative, for the continuous rotation case, the rate of rotation of shaft 124 may be within the range .5 RPM to 5 RPM. The motor and housing may be considered as within the scope of means to support and rotate the gyroscope and accelerometers.

Due to rotation of the shaft 123, and lower extensions 123a, 123b and 123c thereof, the frames 125 and 225 of the gyroscopes and the frames 126 and 226 of the accelerometers are typically all rotated simultaneously about axis 124, within and relative to the sealed housing 118. The signal outputs of the gyroscopes and accelerometers are transmitted via terminals at suitable slip ring structures 125a, 225a, 126a and 226a, and via cables 127, 127a, 128 and 128a, to the processing circuitry at 129 within the instrument, such circuitry for example including that described above, and multiplexing means if desired. The multiplexed or non-multiplexed output from such circuitry is transmitted via a lead in cable 113 to a surface recorder, as for example includes pens 131—134 of a strip chart recorder 135, whose advancement may be synchronized with the lowering of the instrument in the well. The drivers 131a—134a for recorder pens 131—134 are calibrated to indicate bore-hole azimuth, degree of tilt and depth, respectively, and another strip chart indicating bore-hole depth along its length may be employed, if desired. The recorder can be located at the instrument for subsequent retrieval and read-out after the instrument is pulled from the hole.

One specific example of multiple gyroscopes will now be described, other type rate sensors being usable.

Turning now to Fig. 12, the gyroscopes G_1 and G_2 are of compact, highly reliable construction, and each is characterized as having a spinning rotor or wheel (as at 136), and torsion structure defining an inner gimbal. Further, the rotor spin frequency has a predetermined relation to a resonant frequency of the torsion structure. For example, the rotor 136 is typically driven at high speed by synchronous motor 137, through the gimbal which includes mutually orthogonally extending primary and secondary torsion members 138 and 139, also schematically indicated in Fig. 12a. In this regard, motor rotary parts 140 transmit rotation to shaft 141 onto which a sleeve 142 is pressed. The sleeve is joined to arm 143 which is connected via radially extending torsion members 138 to ring 144. The latter is joined via torsion members 139 to rotor or wheel 136. The rotor axis is generally coincident with axis 124. In Figs. 12 and 12a the axes are members of gyroscopes G_1 and G_2 are related as follows:

- Y — direction axis A_1 defined by torsion members 139
- X — direction axis A_2 defined by torsion members 138
- Z — direction axis A_3 defined by shaft 141

Auxiliary elements of G_1 include a magnetic armature 145 affixed to the rotor 136 to rotate therewith; pick-offs 146 and 147 affixed to the case 148 (attached to frame 125) to extend closely

beneath the rotor so as to be inductively activated by the armature as it rotates about the A_3 , (see pick-off coils 146a and 147a) and torque motors 149 and 150 affixed to the case. In Fig. 12, stops 250 on shafts 141 limit rotor gimbaling relative to the shafts, stops, pick-offs and torque motors. See the schematic of Fig. 12b which relates the positions of the torque motors and pick-offs to the armature, in quadrant relationship. The torque motors enable precessional or rebalanced torques to be applied to the rotor, via armature 145, on axes A_1 , and A_2 , which enable use of the gyro as a servoed rate gyro.

The construction is such that the need for ball bearings associated with gimbaling of the rotor is eliminated, and the overall size of the gyroscope is reduced, and its output accuracy enhanced. The speed of rotation of the rotor and the torsion characteristics of the members 138 and 139 are preferably such as to provide a "tuned" or resonant dynamic relationship so that the rotor tends to behave like a free gyro in space. In addition, the angular position of the wheel relative to the housing (i.e. about axes A_1 and A_2) may be detected by the two orthogonal pick-offs (thus to the extent the rotor tends to tilt about axis A_2 toward one pick-off, its output is increased, for example, and to the extent the rotor tends to tilt about axis A_1 toward the other pick-off its output is increased, for example). Therefore, gimbaling of the rotor is accurately sensed, as the gyroscope G_1 and its frame 125 are rotated about axis 124 by motor 122. In practice, the deflection of the wheel is quite limited, due to servo-rebalancing through the torque devices.

The Fig. 12 gyroscope G_2 is shown as having the same construction as G_1 ; however axes A_1 , A_2 and A_3 of the two gyros are related as shown by the schematically orthogonal arrow groups 153 and 154 in Fig. 12. Thus, the axis A_3 of the first gyro G_1 extends parallel to the one axis 124 which is the axis of rotation of the frames 125 and 225 produced by motor 122; and the axis A_3 of the second gyro G_2 is normal to axis 124. The pick-offs 146 and 147 provide means to detect rotor pivoting about at least one, and preferably either, of the input axes IA_1 and IA_2 , in response to such rotation of the gyroscope frame, for each gyro. Thus, the output of either pick-off 146 and 147 of each gyro provides a signal ω_1 , as described in Fig. 1a.

The outputs from the two gyros provide information which enables a "double check," or redundancy, as to azimuth relative to the instrument case or housing. Turning to Fig. 11, as the gyroscope G_2 is rotated about axis 124, its signal output 139a, as detected by pick-off 147, is maximized when its axis A_3 passes through the North-South longitudinal plane, and is least when that axis is closest to being normal to that plane. As the other gyroscope G_1 is rotated about axis 124, its signal output 139b, as detected by its pick-off 147, is maximized when its axis A_3 passes through the North-South longitudinal plane, and is least when that axis A_3 is closest to being normal to the plane. The values 139a and 139b are most accurate when corrected by compensation to correspond to the value ω'_1 discussed above. Thus, for a non-vertical bore-hole, the two gyros will have outputs, and depending upon the latitude of the bore-hole, the two outputs will vary; however, they will tend to confirm each other, one or the other providing a stronger output. One usable gyroscope is Model GAM-1, a product of Societe de Fabrication de Instruments de Mesure, 13 av. M. Ramolfo-Garner 91301 Massy, France.

Further, although each gyroscope G_1 and G_2 is a "two-axis" gyro (i.e. capable of rotation about either axis A_1 , and A_2) it can be operated as a single degree of freedom gyro (i.e. made rotatable as described about only one of the axes A_1 and A_2) through use of the torque motors.

The accelerometer 226, which is simultaneously rotated with the gyroscope, has an output as represented for example at 145 in Fig. 11 under tilted conditions corresponding to tilt of axis 124 in North-South longitudinal plane; i.e., the accelerometer output is maximized when the G_2 gyroscope output indicates South alignment, and again maximized when the gyroscope output indicates North alignment. Figure 10 shows tilt of axis 124 from vertical 146, and in the North-South plane, for example. Further, the accelerometer maximum output is a function of the degree of such tilt, i.e. is higher when the tilt angle increases, and vice versa; therefore, the combined outputs of the gyroscope and accelerometer enable ascertainment of the azimuthal direction of bore-hole tilt, at any depth measured lengthwise of the bore-hole and the degree of that tilt. The operation of accelerometer 126 is the same as that of 226, and is shown at 145a in Fig. 11 both being rotated by motor M at the same rate.

Fig. 13 diagrammatically illustrates the functioning of either accelerometer in terms of rotation of a sensitive axis (indicated by locus 140) in a plane and about axis 124 tilted at angle θ from vertical 146. As the locus rotates through points 144 at the level of the intersection of axis 124 and vertical 146, its rate of change of velocity in a vertical direction is zero; however, as the locus rotates through points 147 and 148 at the lowest and highest levels of its excursion, its rate of change of velocity in a vertical direction is at a maximum, that rate being a function of the tilt angle θ . A suitable accelerometer is that known as Model 4303, a product of Systron-Donner Corporation, of Concord, California, United States of America.

Control of the angular rate of rotation of shaft 123 about axis 124 may be from a surface control equipment indicated at 150, and circuitry 129 connected at 180 with the motor. Means (as for example a rotary table 81) to rotate the drill pipe 110 during well mapping, as described, is shown in Fig. 9.

Referring to Figs. 9 and 16 either gyroscope is characterized as producing an output ω_1 which varies as a function of azimuth orientation of the gyroscope relative to the earth's spin axis, that output

for example being indicated at 209 in Fig. 16 and peaking when North is indicated. Most accurate peaking is indicated when the rate gyroscope output has been compensated as described above. Shaft 123 may be considered as a motor rotary output element which may transmit continuous unidirectional drive to the gyroscopes, or incremental continuous drive to pre-selected angular positions. Alternatively, the shaft may transmit cyclically reversing rotary drive to the gyroscopes, with or without incremental stopping at pre-selected angular positions. Further, the structure 122 in Fig. 9 may be considered as including servo means responsive to the gyroscope output to control the shaft 123 so as to maintain the gyroscopes with predetermined azimuth orientation, i.e. the output axis of gyroscope G_2 for example may be maintained with direction such that the output 209 in Fig. 16 remains at a maximum or any other desired level.

Also shown in Fig. 9 is circuitry 210, which may be characterized as a position pick-off, for referencing the gyroscope and accelerometer outputs to the case or housing 118. Thus, that circuitry may be connected with the motor (as by wiper 211 on shaft 123d turning with the gyroscope frames 125 and 225 and with shaft 123), and also connected with the carrier 118 (as by slide wire resistance 212 integrally attached to the carrier) to produce an output signal at terminal 214 indicating azimuthal orientation of the gyroscopes relative to the carrier. That output also appears at 215 in Fig. 16. As a result, the output as terminal 214 may be processed (as by surface means generally shown at 216 connected to the instrumentation by cable 13) to determine or derive azimuthal data including orientation of the carrier or housing 118 relative to the earth's spin axis. Such information is often required, as where it is desired to know the orientation of well logging apparatus being run in the well.

In this regard, each gyro produces an output as reflected in its gimbaling, which varies as a function of azimuth orientation of the gyro relative to the earth's spin axis. The position pick-off, in referencing the gyroscope to the frame 118 produces an output signal at the pick-off terminal indicating azimuthal orientation of the gyro and accelerometer relative to the carrier or frame.

Item 220 in Fig. 9 may be considered, for example, as well logging apparatus the output of which appears at 221. Carrier 118 supports item 220, as shown. Merely for purpose of illustration, such apparatus may comprise an inclinometer to indicate the inclination of the bore-hole from vertical, or a radiometer to sense radiation intensity in the hole.

It will be understood that the recorder apparatus may be at the instrument location in the hole, or at the surface, or any other location. Also, the control of the motor 129 may be pre-programmed or automated in some desired manner.

Figs. 14 and 15 show the separate and individual use of the gyroscopes G_1 and G_2 (i.e. not together) in combination with drive motors 622 and 722, and accelerometers or tilt sensitive devices 620 and 721, respectively. Other elements corresponding to those in Fig. 9 bear the same numbers but are preceded by a 6 or 7, as respects Figs. 14 and 15. The operations of the gyroscopes G_1 and G_2 in Figs. 14 and 15 are the same as described in Fig. 9.

Figs. 17 and 18 illustrate the use of one angular rate gyroscope 170 to produce an angular rate signal ω_1 having an angular acceleration error 172 in its output wave form 173. That error derives from the servo and cultural noise in rotational modes, as well as start-ups and slow-downs, in incremental mode. A second angular rate gyroscope 174 is rotated with gyroscope 170 (as on a common carrier 175 rotated about an axis 176 generally parallel to the bore-hole 177 as for example is described above). That gyro's sensitive axis is inverted from that of the first gyro, but it has the same angular acceleration sensitivity sign. Accordingly, its output ω_{10} is passed through an inverting circuit 178, so that in its output wave form 179 the same error 180 (due to angular acceleration) shows up, but is inverted. When the outputs of the two gyros are summed at 181, not only do the two errors cancel, but the resultant amplitude is increased, as is clear from resultant wave form 182 seen in Fig. 18. Further the second redundant gyroscope enhances reliability, to enable continued operation in the bore-hole (without requiring a "round trip" pull-out of the string) and avoiding expense, in the event of failure of one gyro in the hole. Summing represents compensation.

Further, in holes with high temperature ranges, such multiple gyros are usable with one adjusted (or its output adjusted) to be optimized at one temperature, another at a second temperature and so forth. One important optimization would be floatation temperature, for instance. One also could take advantage of two gyros having two cant angles, or one without cant and one with, so as to have the best ability to measure various tilts and directions in a diverting bore-hole. Gyros 170 and 174 may be considered to represent such temperature adjusted gyros, or canted gyros.

Fig. 20 illustrates the use of an angular rate gyroscope 170 to produce an angular rate signal ω_1 having an angular acceleration error 173 in its output wave form 173; the same as described above in Fig. 17. An angular accelerometer 190 is rotated with gyroscope 170 (as on a common carrier 175a rotated about an axis 176a generally parallel to the bore-hole 177a, as for example is described above). That accelerometer's output α_{10} includes "error" 192 (due to change in angular acceleration), and is inverted relative to error 172. When the two outputs are summed at 193, the errors cancel, as is clear from the resultant wave form 194. Summing here represents compensation of output ω_1 by the output α_{10} of acceleration 190.

The following commercial devices, as identified, are usable for the described sensors, including angular rate sensors and accelerometers:

Single Axis Rate Sensor

	Vibrating Wire Rate Sensor	Honeywell Model GG1102	
	Jet Stream Rate Gyro (solid state rate sensor)	Hamilton Standard Superjet	
5	Laser Gyro	Honeywell Model GG1324	5
	Sonic Gyro	AC Delco Division of General Motors	
	Nuclear Spin Rate Gyro	Litton NMR Gyros	
	Two Axis Rate Sensor		
10	Magnet hydrodynamic Rate Sensor (MHD)	Honeywell Model GG250	10
	Dual Axis Rate Transducer (DART)	British Aircraft Co. Model 408	
	Dynamically Tuned Gyro (DTG)	Incosym, Inc. Incoflex	
15	Dynamically Tuned Gyro (DTG)	Northrop Model GT—B2	15
	Differentiated Position Gyro (ESG)	North American Micron Gyro	
	Differentiated Free Gyro	Systron Donner PKF—3	
	Combination Rate Sensor and Accelerometer		
20	Rate Sensor and Accelerometer	Litton Multisensor	20
	Angular Accelerometer		
	Angular Accelerometer	Systron Donner Model 4596	
	Stable Platforms (Differentiate Angular Position To Get Angular Rate)		
	Gimbal Stable Platform	Litton AHARS: LTR—80	
25	Strapdown Stable Platform	Northrop NIS—210	25

Fig. 19 shows, generally, a carrier 10 in a bore-hole 11, a drive 13 to rotate the carriage and a power source P to selectively energize the drive, if rotation is desired. These elements are suspended in the bore-hole, to be lifted and lowered, as in Fig. 1.

Within the carrier are signal sources indicated as blocks 200—204 to generate signals ω , a , α , T and t , as described above. Those signals are selectively transmitted via switches 200a -- 204a to compensation circuitry 206, for selective compensation, for example as described above. The compensated signals are then processed in a computer 207 to derive accurate indications of tilt and azimuth, as shown. A master control 210, as at the surface, is operable to control the switches, as desired.

The apparatus and method described herein is useful for both mapping or surveying of a bore-hole, and also for steering of a tool in the hole, as for example assisting in guiding of a drill bit to change its direction. Fig. 21 shows the instrument housing 210' (corresponding to housing 10 in Fig. 1a, housing 110 in Fig. 9, and housing 175 and 175a in Figs. 17 and 20) lowered or pumped down a well or bore-hole 211' and landed at 212' on an angularly locating latching seat structure 212'a integral with drill stem 213', and retaining the housing in a selected angular position relative to the stem. Drilling mud or fluid passes downwardly through openings 214' in the seat structure, for access to the drill bit 215' and lifting of cuttings in the annulus 216. Rotation of the drill stem rotates the instrument to provide the rotary motion or input to the instrument. Thus, the instrument enables sensing of the azimuth and tilt of the drill stem and bore-hole at the drill location. Retrieval of the instrument is enabled by wire line 214,

wherever required. Once the tilt, depth and azimuth of the hole at drill location is known, a shoe or other device may be employed in the hole to deflect or steer the drill in the desired direction. Hole depth may be determined from the length of drill pipe in the hole. The drill bit is indicated at 230.

Fig. 22 is like Fig. 21, except that the instrument case 210a' is mounted to the drill stem, as for example by ribs 216' or other means, allowing passage of drilling fluid downwardly at 217' to the drill bit. Signals are transmitted upwardly to the surface from the instrument 210a as via suitable means. For example, a valve 218' in the path of the fluid may be opened or closed (in accordance with azimuth and tilt data from instrument 210a'), and that opening and closing movement sensed at the surface via fluid flow detector 220.

Fig. 24 shows an angular rate sensor or sensors 216 such as appear at 16 in Fig. 1a; a linear accelerometer or accelerometers 217 as appear at 17 in Fig. 1a; and an angular rate accelerometer or accelerometer 250 as appear at 150 in Fig. 1a. A common drive to rotate these devices in a bore-hole 11 appears at 213 and corresponds to drive 13 in Fig. 1a. The difference over Fig. 1a lies in the cant of the sensor or sensors 216 relative to the axis 214 of rotation (see angle α , or the cant angle α of the sensitive axis 216a relative to horizontal or relative to the devices 217 and 250 which are not canted).

Fig. 25 is like Fig. 24, except that device 217 is also canted, at angle γ ; Fig. 26 is like Fig. 24, except that device 250 is also canted at angle β ; Fig. 27 is like Fig. 27 except that device 216 is not canted relative to axis 214; and Fig. 28 is like Fig. 27 except that device 217 is not canted relative to axis 214. Angles α , γ and β may or may not be the same.

A free gyroscope may also be combined with the angular rate sensor or gyroscope disclosed herein, in the manner described in U.S. Patent 4,192,077, and for that purpose the block 17 may be considered to represent:

- a) an angle reference device (such as a free gyroscope) carried for movement along a travel axis in a bore hole, that device having a calibratable component,
- b) first means (such as an angular rate sensor) having an output for effecting calibration of that component and
- c) control means connected with the first means to cause the first means to periodically effect calibration of that component.

Block 17 may also be considered to represent a dual gimbaled angular rate gyroscope system as disclosed in U.S. Patent 4,197,654, with the output of either or both gyroscopes compensated as disclosed herein. As disclosed in that prior patent, two angular rate gyros are respectively rotatable about axes which are mutually perpendicular.

In the above, the sensors (as for example are shown in Figs. 1a, 9 and other views, may be rotated by the indicated drive motor, or motors, or the tubing or drill stem, in any of several modes, including continuously, incrementally, cyclically, and forwardly and reversely.

CLAIMS

1. In apparatus for determining azimuth and tilt in a bore-hole,
 - a) a carrier movable in the bore-hole,
 - b) angular rate sensor means on the carrier and having an output,
 - c) an acceleration sensor means on the carrier and having an output,
 - d) circuit means operatively connected with the sensor means for compensating signals derived from the output of at least one of the sensor means in accordance with the values of signals derived from the output of the other sensor means, to produce compensated signals.
2. The apparatus of claim 1 wherein said circuit means is connected with the sensor means to adjust angular rate signals derived from the output of the angular rate sensor thereby to compensate for acceleration effects associated with acceleration signals derived from the output of the acceleration sensor means; so as to produce corrected angular rate values.
3. The apparatus of claim 2 wherein said circuit means includes summing circuitry to sum an angular rate signal ω along a selected coordinate axis, and a signal D_a along said axis, where "D" is a constant and "a" is a value corresponding to the output of the acceleration sensor means, along said axis.
4. The apparatus of claim 2 wherein said circuit means includes summing circuitry to sum angular rate signals ω_1 , ω_2 and ω_3 along three selected axes associated with the angular rate sensor means, with, respectively, acceleration signals $D_1 a_1$, $D_2 a_2$ and $D_3 a_3$ along said axes, where D_1 , D_2 and D_3 are constants and a_1 , a_2 and a_3 are values corresponding to acceleration outputs along said three selected axes, respectively, of the acceleration sensor means.
5. The apparatus of claim 1 wherein said circuit means is on the carrier.
6. The apparatus of claim 1 wherein said circuit means is outside the bore hole.
7. The apparatus of claim 1 wherein part of said circuit means is on the carrier and part of the circuit means is outside the bore hole.
8. The apparatus of claim 1 including temperature compensating circuit means to compensate signals derived from at least one of the sensor means in accordance with temperature changes encountered in the bore hole.

9. The apparatus of claim 8 wherein said temperature compensating circuit means is on the carrier and is operatively connected with the sensor means.
10. The apparatus of claim 8 wherein said temperature compensating circuit means is operatively connected with both sensor means b) and c) of claim 1.
11. The apparatus of claim 1 including time compensating circuit means to compensate signals derived from at least one of the sensor means b) and c) of claim 1 in accordance with time values.
12. The apparatus of claim 11 wherein said time compensating circuit means is operatively connected with the one sensor means.
13. The apparatus of claim 11 wherein said time compensating circuit means is operatively connected with both sensor means b) and c) of claim 1.
14. The apparatus of claim 1 wherein means is provided to rotate the carrier in the bore-hole and about an axis extending generally in the direction of the bore-hole.
15. The apparatus of claim 4 including coordinate conversion circuit means operatively connected with said acceleration sensor means to convert outputs of the acceleration sensor means along three axes of said values a_1 , a_2 and a_3 along said three selected axes.
16. The apparatus of claim 1 including means operatively connected with said circuit means to receive said corrected angular rate values and to produce an output which varies as a function of azimuth orientation of the angular rate sensor means.
17. The apparatus of claim 16 including means to rotate both said angular rate sensor means and said acceleration sensor means in the bore hole, and about an axis extending generally in the direction of the bore hole.
18. The apparatus of claim 1 wherein said circuit means is connected with the sensor means to adjust acceleration signals derived from the output of the acceleration sensor means to compensate for angular rate effects associated with angular rate signals derived from the output of the angular rate sensor means, thereby to produce corrected acceleration values.
19. The apparatus of claim 18 including means operatively connected with said circuit means to receive said corrected acceleration values and to produce an output which varies as a function of tilt of the acceleration sensor means.
20. The apparatus of claim 19 including means to rotate both said angular rate sensor means and said acceleration sensor means in the bore hole, and about an axis extending generally in the direction of the bore hole.
21. The apparatus of claim 1 wherein said angular rate sensor means comprise rate gyroscope means.
22. The apparatus of claim 20 wherein said rate gyroscope means comprises two rate gyroscopes.
23. The apparatus of claim 1 wherein said angular rate sensor means is canted relative to an axis defined by the bore hole.
24. The apparatus of claim 1 wherein said acceleration sensor means is canted relative to an axis defined by the bore hole.
25. In apparatus for determining azimuth and tilt, in a bore hole
- a carrier movable in the bore-hole,
 - angular rate sensor means on the carrier and having an output,
 - an acceleration sensor means on the carrier and having an output, and
 - circuit means operatively connected with the sensor means for compensating signals derived from the output of at least one of the sensor means, for use of such compensated signals in conjunction with signals derived from the other of the sensor means.
26. The apparatus of claim 25 wherein said d) means comprises temperature compensation circuitry.
27. The apparatus of either of claims 25 and 26 wherein said d) means comprises time compensation circuitry.
28. The apparatus of any of claims 25, 26 or 27 wherein said d) means comprises co-ordinate transformation circuitry.
29. The apparatus of any of claims 25, 26, 27 or 28 wherein said d) means is operatively connected with both of the sensor means.
30. The apparatus of claim 1 wherein the acceleration sensor means comprises a second angular rate sensor means.
31. The apparatus of claim 30 wherein said b) and c) angular rate sensor means each comprises a rate gyroscope.
32. The apparatus of claim 30 wherein said circuit means includes circuitry to sum the outputs of the b) and c) sensor means to substantially cancel error due to angular acceleration.
33. The apparatus of claim 31 wherein said circuit means includes circuitry to sum the outputs of the b) and c) gyroscopes to substantially cancel error due to angular acceleration and also to increase the gain of the summing circuitry output.
34. The apparatus of claim 1 wherein said circuit means is connected with the sensor means to adjust angular rate signals derived from the output of the angular rate sensor thereby to compensate for angular acceleration effects associated with angular acceleration signals derived from the output of the

acceleration sensor means, so as to produce corrected angular rate values.

35. The apparatus of claim 34 wherein said circuit means includes summing circuitry to sum an angular rate signal ω along a selected coordinate axis, and a signal $K\alpha$ along said axis, where "K" is a constant and " α " is a value corresponding to the output of the acceleration sensor means, about said axis.

36. The apparatus of claim 34 wherein said circuit means includes summing circuitry to sum angular rate signals ω_1 , ω_2 and ω_3 along three selected axes associated with the angular rate sensor means, with, respectively, acceleration signals $K_1\alpha_1$, $K_2\alpha_2$ and $K_3\alpha_3$ along said axes, where K_1 , K_2 and K_3 are constants, and α_1 , α_2 and α_3 are values corresponding to angular acceleration outputs along said three selected axes, respectively, of the acceleration sensor means.

37. The apparatus of claim 34 including temperature compensating circuit means to compensate signals derived from at least one of the sensor means in accordance with temperature changes encountered in the bore-hole.

38. The apparatus of claim 37 wherein said temperature compensating circuit means is on the carrier and is operatively connected with the sensor means.

39. The apparatus of claim 37 wherein said temperature compensating circuit means is operatively connected with both sensor means b) and c) of claim 1.

40. The apparatus of claim 37 including time compensating circuit means to compensate signals derived from at least one of the sensor means b) and c) of claim 1 in accordance with time values.

41. The apparatus of claim 40 wherein said time compensating circuit means is operatively connected with the one sensor means.

42. The apparatus of claim 40 wherein said time compensating circuit means is operatively connected with both sensor means b) and c) of claim 1.

43. The apparatus of claim 37 including means to rotate the carrier in the bore-hole and about an axis extending generally in the direction of the bore-hole.

44. The apparatus of claim 36 including coordinate conversion circuit means operatively connected with said acceleration sensor means to convert outputs of the acceleration sensor means along three axes to said values α_1 , α_2 and α_3 along said three selected axes.

45. The apparatus of claim 40 including means operatively connected with said circuit means to receive said corrected angular rate values and to produce an output which varies as a function of azimuth orientation of the angular rate sensor means.

46. The apparatus of claim 1 wherein said acceleration sensor means includes:

- i) a linear acceleration sensor means, and
- ii) an angular acceleration-sensor means.

47. The apparatus of claim 46 wherein said circuit means is connected with the sensor means to adjust angular rate signals derived from the output of the angular rate sensor thereby to compensate for linear and angular acceleration effects associated with acceleration signals derived from the output of the acceleration sensor means, so as to produce corrected angular rate values.

48. The apparatus of claim 47 wherein said circuit means includes summing circuitry to sum an angular rate signal ω along a selected coordinate axis, and a signal Da along with axis, where "D" is a constant and "a" is a value corresponding to the output of the linear acceleration sensor means, along said axis, and also to sum said angular rate signal ω and a signal $K\alpha$ along said axis, where "K" is a constant and " α " is a value corresponding to the output of the angular acceleration sensor means about said axis.

49. The apparatus of claim 34 wherein said circuit means includes summing circuitry to sum angular rate signals ω_1 , ω_2 and ω_3 along three selected axes associated with the angular rate sensor means, with, respectively, linear acceleration signals D_1a_1 , D_2a_2 and D_3a_3 along said axes, where D_1 , D_2 and D_3 are constants, and a_1 , a_2 and a_3 are values corresponding to acceleration outputs along said three selected axes, respectively, of the acceleration sensor means, and also to sum said rate signals ω_1 , ω_2 and ω_3 along said three selected axes with, respectively, angular acceleration signal $K_1\alpha_1$, $K_2\alpha_2$ and $K_3\alpha_3$ along said axes, where K_1 , K_2 and K_3 are constants, and α_1 , α_2 , and α_3 are values corresponding to angular acceleration outputs along said three selected axes, respectively, of the acceleration sensor means.

50. The apparatus of claim 47 including temperature compensating circuit means to compensate signals derived from at least one of the sensor means in accordance with temperature changes encountered in the bore-hole.

51. The apparatus of claim 50 wherein said temperature compensating circuit means is on the carrier and is operatively connected with the sensor means.

52. The apparatus of claim 50 wherein said temperature compensating circuit means is operatively connected with both sensor means b) and c) of claim 1.

53. The apparatus of claim 47 including time compensating circuit means to compensate signals derived from at least one of the sensor means b) and c) of claim 1 in accordance with time values.

54. The apparatus of claim 53 wherein said time compensating circuit means is operatively connected with the one sensor means.

55. The apparatus of claim 53 wherein said time compensating circuit means is operatively

connected with both sensor means b) and c) of claim 1.

56. The apparatus of claim 50 wherein means is provided to rotate the carrier in the bore-hole and about an axis extending generally in the direction of the bore-hole.

57. The apparatus of claim 49 including coordinate conversion circuit means operatively
5 connected with said acceleration sensor means to convert outputs of the angular acceleration sensor means along three axes to said values α_1 , α_2 and α_3 along said three selected axes. 5

58. The apparatus of claim 53 including means operatively connected with said circuit means to receive said corrected angular rate values and to produce an output which varies as a function of azimuth orientation of the angular rate sensor means.

10 59. The apparatus of claim 1 wherein said c) means includes a drive to effect continuous rotation of the sensor means. 10

60. The apparatus of claim 1 wherein said c) means includes a drive to effect incremental rotation of the sensor means.

61. The apparatus of claim 1 wherein said c) means includes a drive to effect cyclical rotation of
15 the sensor means. 15

62. The apparatus of claim 1 wherein said c) means includes a drive to effect alternate forward and reverse rotation of the sensors.

63. The apparatus of claim 1 wherein said c) means comprises a second angular rate sensor means.

20 64. The apparatus of claim 63 wherein said b) and c) sensor means comprises angular rate gyroscopes. 20

65. The apparatus of claim 64 wherein said circuit means includes an inverter to invert an error signal in the output of the second gyroscope, and a summing circuit to sum the outputs of the two gyroscopes to cancel an error signal in the output of the first gyroscope by summation with the inverted error signal in the output of the second gyroscope. 25

66. The apparatus of claim 1 wherein said c) means comprises an angular accelerometer.

67. The apparatus of claim 1 wherein said circuit means is connected with the sensor means to adjust linear acceleration signals derived from the output of the acceleration sensor thereby to compensate for angular rate effects associated with angular rate signals derived from the output of the
30 angular rate sensor means, so as to produce corrected linear acceleration values. 30

68. The apparatus of claim 1 wherein said circuit means is connected with the sensor means to adjust angular acceleration signals derived from the output of the acceleration sensor thereby to compensate for angular rate effects associated with angular rate signals derived from the output of the angular rate sensor means, so as to produce corrected angular acceleration values.

35 69. The apparatus of claim 1 wherein said circuit means is connected with the sensor means to adjust angular rate signals derived from the output of the angular rate sensor thereby to compensate for linear and angular acceleration effects associated with linear and angular acceleration signals derived from the output of the acceleration sensor means, so as to produce corrected angular rate values. 35

70. The apparatus of claim 1 including an angle reference device on the carrier and connected to
40 be calibrated in accordance with the output of the angular rate sensor means. 40

71. The apparatus of claim 70 wherein said angle reference device comprises a free gyroscope.

72. The method of mapping a bore-hole, including

a) suspending within the hole angular rate sensor means and acceleration sensor means, each of
45 said sensor means having an output, 45
b) rotating said sensor means in the bore-hole and
c) operating said sensor means to provide outputs, and
d) using the output from one sensor means to compensate the output of the other sensor means.

73. The method of claim 72 wherein angular rate signals are derived from the output of the angular rate sensor means and acceleration signals are derived from the output of the acceleration sensor means, and said d) step includes using said acceleration sensor signals to adjust said angular rate signals to correct same. 50

74. The method of claim 72 wherein said signals have associated co-ordinates, and including the step of adjusting the co-ordinates of said angular rate and acceleration signals to conform to the co-ordinates of the other of said angular rate and acceleration signals.

75. The method of claim 72 wherein said sensor means have sensitive axes, and said suspending
55 step includes orienting the sensitive axis of at least one sensor means in general alignment with the bore-hole. 55

76. The method of claim 75 wherein said suspending step includes orienting the sensitive axes of multiple of said sensor means in predetermined relation with the bore-hole.

77. The method of claim 72 wherein said sensor means have sensitive axes, and said suspending
60 step includes orienting the sensitive axis of at least one of the sensor means at a cant angle relation to the bore-hole direction of elongation. 60

78. The method of claim 72 wherein said suspending step includes orienting the sensitive axes of multiple of said sensor means at cant angles, respectively, to the bore-hole direction of elongation.

65 79. The method of claim 72 wherein signals are derived from said sensor output, and including the 65

step of compensating certain of said signals in accordance with temperature encountered in the bore-hole.

80. The method of claim 79 wherein the signals derived from the outputs of the angular rate and acceleration sensors are temperature compensated.

81. The method of claim 72 wherein signals are derived from said sensor outputs, and including the step of compensating certain of said signals in accordance with time values.

82. The method of claim 81 wherein the signals derived from the outputs of the angular rate and acceleration sensors are time value compensated.

83. The method of claim 72 wherein said b) step rotation is about an axis extending generally in the direction of the bore-hole.

84. The method of claim 72 including employing the outputs of the sensor means, including said compensated output, to determine azimuth and degree of tilt of the bore-hole at the location of the sensor means therein when the outputs are produced.

85. The method of claim 72 wherein acceleration signals are derived from the output of the acceleration sensor means, and angular rate signals are derived from the output of the angular rate sensor means, and said d) step includes using said angular rate signals to adjust said acceleration signals, to modify same.

86. The method of claim 72 wherein said angular rate sensor means comprises angular rate gyroscope means, and including the step of allowing said gyroscope means to turn about a sensitive axis in response to said b) step rotation, to produce said output.

87. The method of claim 72 wherein said rotation is carried out continuously.

88. The method of claim 72 wherein said rotation is carried out incrementally.

89. The method of claim 72 wherein said rotation is carried out cyclically.

90. The method of claim 72 wherein said rotation is carried out alternatively forwardly and reversely.

91. The method of claim 73 wherein said acceleration signals are derived as linear acceleration signals.

92. The method of claim 73 wherein said acceleration signals are derived as angular acceleration signals.

93. The method of claim 73 wherein,

i) certain of said acceleration signals are derived as linear acceleration signals, and

ii) other of said acceleration signals are derived as angular acceleration signals.

94. The method of claim 91 wherein said angular acceleration signals are derived from second angular rate sensor means rotated in conjunction with rotation of said first mentioned angular rate sensor means.